Chapter 4

IRRIGATION AND WATER MANAGEMENT IN THE INDUS BASIN: INFRASTRUCTURE AND MANAGEMENT STRATEGIES TO IMPROVE AGRICULTURAL PRODUCTIVITY

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Introduction

Pakistan's large and complex agricultural sector is heavily dependent on irrigation and the hydrological dynamics of the Indus Basin Irrigation System (IBIS), supported by a massive configuration of infrastructure involving both surface water and groundwater irrigation. This system faces a number of major challenges: a rapidly increasing demand for water for industry and urban use without commensurate or adequate infrastructure investment; diminishing water availability in many regions; poor and often controversial allocations of water across provinces; inadequately coordinated management of surface and groundwater; large fluctuations in annual rainfall; and the effects of long-term changes in climate. A recent review of the water resources in Pakistan identifies five key areas of need for policy makers to focus on: (1) construction of new and major infrastructure, and rehabilitation and modernization of existing infrastructure; (2) improvement of efficiency of the water system through better canal management, on-farm water management, and judicious use of scarce groundwater; (3) revision of water charges to better reflect the economic costs of providing irrigation water; (4) lack of awareness of impacts of climate change as construction projects are undertaken; and (5) investment in capacity building and knowledge management (FoDP-WSTF 2012). These issues and options are additionally reviewed well in several recent publications, including Laghari, Vanham, and Rauch (2012), Chaudhry (2010), Qureshi (2011), and Briscoe and Qamar (2006).

This chapter provides an economic assessment of investment, policy, and improved management options that encourage higher-valued and sustainable use of water resources in Pakistan. The presentation follows Laghari, Vanham, and Rauch (2012), who argue that solutions to water resources issues can be split into supply-side options (reservoir management; wastewater infrastructure; desalination and recycling of wastewater; and land use planning, soil conservation, and flood management) and demand-side options (joint management of surface and groundwater, rehabilitation and modernization of existing infrastructure, increased water productivity for agriculture, crop planning and diversification, economic instruments, and changing food demand patterns and limiting post-harvest losses).

The chapter focuses mainly on the economic dimensions of five major solutions they propose, which are either directly related to agriculture or can be achieved by changes within water resources institutions. It combines an analysis of the determinants of on-farm productivity and technical efficiency with an economy-wide model, examining the following solutions in depth: (1) reservoir management, (2) coordinated management of surface and groundwater, (3) rehabilitation and modernization of existing infrastructure, (4) increased water productivity for agriculture, and (5) economic instruments.

The analyses permit us to look at the proposed solutions from more varied economic perspectives than have been provided in the literature so far. Specifically, to help direct investment and policies to areas where they will have the highest impacts, the analysis provides estimates of the relative benefits of each solution. Moreover, it allows us to consider how these alternative solutions affect water supply and show how cropping patterns might change in favor of greater cotton cultivation at the expense of wheat production, thereby affecting a key food security priority in the country.

The second section begins by providing an overview of key issues in Pakistan's water resources sector. The third section assesses the benefits of large-scale storage to the IBIS by simulating the effects of the proposed Diamer-Bhasha Dam. These results are provided under four climate change scenarios to show effects on the overall economy and on water use by crops. (Annex C discusses the implications for income distribution.) The fourth section then uses our model to explore alternative investments and policies that can improve performance of the IBIS. Specifically, it looks at the effects of reducing losses in distribution from lining watercourses, the effects of better-timed deliveries in the surface water system, which produces the same responsiveness to demand that groundwater provides, and the effects of allowing water trading in excess of the provisions of the 1991 Water Accord. These are compared singly and in combination with the Diamer-Bhasha Dam benefits. The sections also look at the effects on gross domestic product (GDP) and on water use by crops. The fifth section examines the conjunctive use of groundwater versus surface water in an analysis based on data from Round 1.5

of the Rural Household Panel Survey (RHPS), conducted in 2012 (IFPRI/IDS 2012; see Chapter 1). The sixth section reflects on these findings and provides concluding remarks.

Overview of Key Issues in the Water Resources Sector

The water resources sector in Pakistan has a long history of development, with political objectives often being a central part of the storyline. The first canals were developed by the British Raj in the second half of the 19th century to reward political supporters and allies from the Punjab, provide a stable environment against possible Russian intrusion from Central Asia, and create a breadbasket as protection from the recurring famines in eastern India (GoP 1960; Lieftinck 1968; Chaudhry 2010; Bisht 2013). Thus began the development of the largest contiguous irrigated system in the world.

However, in 1947 the hydrology of the vast Indus River basin was ignored in boundary decisions that carved out the independent nations of Pakistan and India. The headwaters of the Indus River were left in India, while the main productive lands went to Pakistan, leaving the country with a permanent sense of being lower riparian (Bisht 2013). This tension led to an extended negotiation between India and Pakistan, facilitated by the World Bank, that resulted in the Indus Water Treaty in 1960. According to provisions of the treaty, water was diverted to India from three eastern rivers (the Ravi, Sutlej, and Beas Rivers) in return for the development of a series of dams to permit Pakistan to capture water that would otherwise have flowed unused into the Arabian Sea (although those flows would also support a larger delta than currently exists). Additionally, link canals were built to move 20 million acre-feet (MAF) from the western to the eastern rivers, which had ceded water to India (Chaudhry 2010; FoDP-WSTF 2012). While three significant dams were built, little storage has been added since the 1970s. Indeed, there is only 30 days' worth of storage in Pakistan, versus about 1,000 days on the Colorado River in the United States and a similar amount in the Murray Darling Basin in Australia (FoDP-WSTF 2012).

Water allocation issues were no less contentious within Pakistan. The Water Accord of 1991, which resulted from a highly sensitive political compromise, allocates Indus basin waters across the four provinces in Pakistan and mandates that current dams be managed with a priority for irrigation, even though hydropower has been a progressively greater contributor of value from large storage dams (Amir 2005; Davies 2012). Moreover, the Water Accord allocates a higher amount of surface water per irrigated acre to Sindh than in the other provinces, which was in line with historical diversions (Lashari et al. 2013). Additionally, some of the higher flows to the Sindh are to keep seawater out of the delta and help preserve wetlands. Balochistan and Khyber Pakhtunkhwa (KPK) cannot use their current allocations under the accord due to a lack of infrastructure, although they were given access to water in anticipation of the completion of certain projects that had been started.

Since the 1960s, increases in irrigation and the expansion of irrigated areas have played a major role in Pakistan's agricultural and economic growth. The total irrigated area nearly doubled between 1960 and 2010, from 10.4 to 20.6 million hectares, because of expanded surface water diversions of about 20 MAF and the growth in water extracted by tube wells by 36.1 MAF over these 50 years (Lieftinck Report 1968; Chaudhry 2010). In 2010, according to the Agricultural Census, 36 percent of irrigated land was watered solely with canal water, and 41 percent with canal and tube well water, while 18 percent was irrigated solely with tube well water (GoP 2010). Other forms of irrigation, such as wells, canals with wells, and tanks, accounted for the remaining 5 percent. About 60 percent of irrigated water available at farm gate comes from canal water; the remaining 40 percent is supplied by groundwater (World Bank 2004), while in drought years the proportion can rise to 50 percent (Chaudhry 2010).

The number of tube wells in the IBIS, and particularly in the Punjab, has grown dramatically since the Salinity Control and Reclamation Programs (SCARPs) began in the 1960s to improve drainage. Using groundwater as a supplement to the surface water *warabandi* system produces several benefits.[1] In addition to providing a buffer during droughts, it also permits farmers to better match supply and demand for water. In some cases, farms are entirely dependent on groundwater, as surface water is either insufficient or nonexistent. This is most prevalent in the tail ends of watercourses (or secondary canals) or outside the command areas of the IBIS. However, there is growing understanding that the current reliance on groundwater is unsustainable, and thus for long-term food security, surface water resources will need to be used more judiciously.

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[1] "The *warabandi* is a rotational water distribution method whereby water is allocated to each farmer typically once a week—hence the frequency of irrigation is at most once per week. . . . The duration of irrigation is determined pro-rata with area. Hence for example in the Punjab a farmer will typically receive 19 minutes of water per acre of land" (Anwar and Aslam 2015).

Examining the overall water balance in the IBIS can be useful.[2] Annual precipitation within Pakistan and in the Indus River basin averages 166 MAF, of which about 82 MAF, or almost 50 percent, goes directly into use by vegetation (green water). The remainder goes into the surface water system, either directly as rainfall or later through snowmelt or glacial runoff. The 82 MAF of precipitation represents about 55 percent of the 150 MAF of water required by crops; 30 percent of the remaining water requirement comes from surface water, and 15 percent from groundwater. Groundwater supports crop water requirements with less applied water, because 53 percent of deliveries are used productively as opposed to 45 percent from surface water.

An average of about two-thirds (102 MAF) of the total water flow in the Indus basin is diverted to canals. Of this diverted water, the 45 percent noted above goes for productive uses, and the remainder goes to Indus treaty allocations to India (8.4 MAF) or groundwater recharge (36.1 MAF) (Chaudhry 2010). The flows into the Arabian Sea are about 40 MAF on average but vary substantially from year to year, as the following discussion will show. These flows to the delta near Karachi need to be at least 8.6 MAF per year to maintain environmental sustainability and to prevent incursion of seawater into the Indus basin delta. Alternatively, an annual minimum flow of 3.6 MAF with an added 25 MAF every five years is needed to meet the requirements for a healthy Indus delta (FoDP-WSTF 2012).

Figures 4.1 and 4.2 show water flows in the Indus, by year and within a given year, and indicate some of the challenges to managing and using those flows productively. Figure 4.1 shows canal diversions and flows to the Arabian Sea from 1975/1976 to 2010/2011. Four elements are included in the figure: the diversions to the canals in kharif and rabi, and the surplus flows to the sea in each season. The figure shows that the variations in total flows can be large, ranging from 80 MAF in drought years to over 180 MAF during years when snowmelt and precipitation are at their highest. The diversions to canals, seen in the bottom two portions of each bar, are limited in kharif by the capacity of canals to handle the available water flowing through the Indus. The diversions in rabi are lower, so the canal capacity is greater than the volume of water available during this part of the year.

The most variable flow is the surplus to estuaries during kharif (the monsoon season). These can range from virtually nothing to very large flows when the volume from snowmelt and rainfall is high, and these flows cannot be stored or diverted for use in irrigation. For example, in the early years of the

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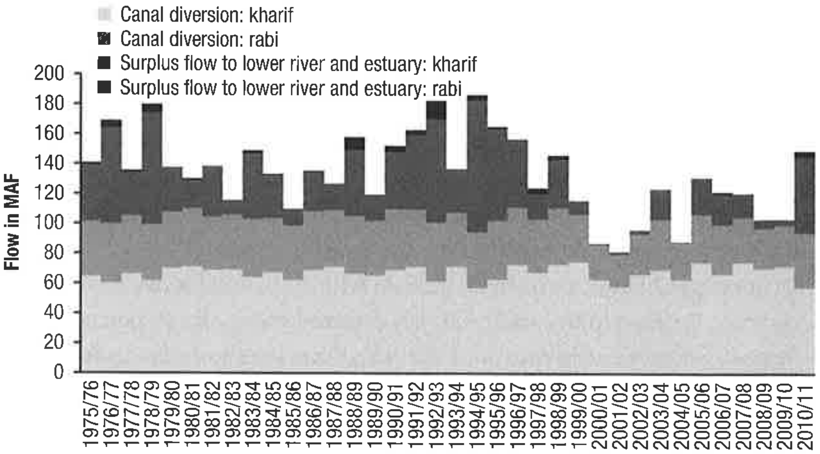
[2] These estimates are drawn from Laghari, Vanham, and Rauch (2012) and Chaudhry (2010).

FIGURE 4.1 Diversion of Indus River flow to canals and surplus flow by season, 1975/1976–2010/2011



Source: Authors, based on data from GoP (various years), *Pakistan Statistical Yearbook.*
Note: MAF = million acre-feet.

2000–2009 decade, total water flows into the Indus basin dropped sharply because of drought, reducing availability of water at the tail end of the system. The kharif season canal diversions were 3.8 MAF (6 percent) lower during the drought period than the long-term average. The rabi shortfalls were much larger, at 11.8 MAF. Surplus flows fell drastically, by 95 percent in the kharif season and 99 percent in rabi. But in 1995/1996 and 2010/2011, monsoons and snowmelt came when storage was already full or came in high concentrations in a short period such that the water could not be retained and large flows had to be released into the sea.[3]

Figure 4.2 shows the flows into and out of the Tarbela Dam, which is the largest storage facility in the system. Over three years, from 2008 to 2010, inflows to the reservoir were low from October through April, while outflows exceeded inflows by small volumes. As a result, storage dropped during these months, which make up the rabi season. The main demand for water is for irrigation of wheat during these months, especially from January to April, and this crop thus faces a lack of water. The crop water requirements in kharif are estimated to be 46 MAF versus 30 MAF in rabi, a 50 percent higher demand in the summer season (Ahmad 2005; FoDP-WSTF 2012). However, because nearly 80 percent of

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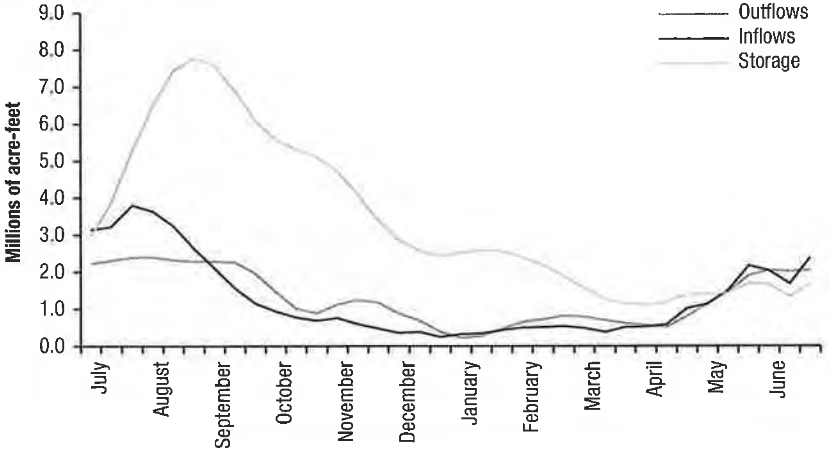
[3] A heavy monsoon in 2010 caused some of the worst floods ever recorded in Pakistan, devastating crops and livelihoods (Dorosh, Malik, and Krausova 2011).

FIGURE 4.2 Average reservoir inflows, outflows, and storage levels in Tarbela Dam, 2008–2010



Source: Davies (2012).

precipitation and inflows into the IBIS occur from April through September, the relative growth in crop production and water demand could alter the use of water during kharif and change the amount available for use later in the year.

Beginning in April, the outflows rise, but inflows rise more rapidly, so the volume stored in the reservoir rises, slowly from April to June and then rapidly in July and August as the snowmelt and monsoon rains reach their peaks. The reservoir is full by the end of August. Outflows grow in proportion to the kharif season's needs, which are at their highest during the summer, but the high inflows from snowmelt and monsoons also require management of releases beyond the immediate need for irrigation. Of course, with climate change, if the monsoon occurs later in the year, the reservoir's ability to manage the excess water is limited, and floods can be more damaging.

Figures 4.1 and 4.2 show that the monsoon rainfall and snowmelt are concentrated in the period from June to August, but use could be spread across the entire year, so there is a need for storage. The main storage infrastructure developed to date consists of dams on the Indus and Jhelum Rivers, which were built shortly after the Indus Water Treaty. Little volume has been added to these dams since the original construction, but much loss in capacity has occurred from sedimentation. Archer et al. (2010) estimate that storage has decreased 28 percent in Tarbela and 20 percent in Mangla, although with the raising of the height of the Mangla Dam, there is now greater capacity in that reservoir. In addition to sedimentation, some estimates of the effects of climate change suggest that smaller water flows are occurring in the spring and summer, even with higher total rainfall, because of a shifting season and lower flows from snowmelt (Laghari, Vanham, and Rauch 2012). For example, Immerzeel, Beek, and Bierkens (2010) suggest that upstream water supply will decline in the Indus by 8.4 percent starting in 2046. This suggests the need to examine the impacts of greater reservoir capacity more closely.

Economic Effects of Expanded Storage: Diamer-Bhasha Dam and Climate Change

This section examines the value of adding reservoir capacity to the IBIS using a whole-economy simulation model (the CGE-W). It presents that model and its baseline solution and looks at the economic benefits of adding storage using the multipurpose Diamer-Bhasha Dam project (described in detail below) as an example. The section highlights GDP benefits under various climate change outcomes, along with water allocation and household income effects. The income effects are presented in Annex C.

The Computable General Equilibrium–Water (CGE-W) Model for Pakistan. The whole-economy model used in this analysis links an economic model with several water modules, drawing on the strengths of both approaches. The suite of models is called, collectively, the computable general equilibrium–water (CGE-W) simulation model for Pakistan. The CGE-W modeling framework and its underlying philosophy are described in Robinson and Gueneau (2014). The model provides a flexible and robust framework for linking and integrating separate economic and water models.

In our simulation, we run the CGE-W model dynamically from 2008 to 2050. In the model, water shortages affect only the agricultural sector and hydropower. Shortages are treated as shocks to total factor productivity in the production functions for crops, proportional to the shock in actual yields. Hydropower output varies with the water level in the reservoirs, and adds to the supply of energy for the general economy. Each year, the CGE model is run in a two-step procedure. It is first solved with average historical water stress to determine farmer decisions on cropping patterns based on expected water availability and economic trends. Then the actual inflows (provided by an external hydrology model, given climate information) are distributed to different canal commands, and water allocation and stress modules allocate available water to different crops based on the impact of water stress on yields and crop values. Finally, the CGE model is solved a second time given the optimal yields derived from the calculated shortages, assuming that the allocation of land to crops is fixed and the model solves for the final values of all economic variables. (Appendix A gives details of each component of this framework.)

The Baseline Simulation. To examine the effects of new storage, a baseline solution is generated using a number of exogenously varied growth rates, which then permits variations from the addition of Bhasha Dam and changes from several climate change scenarios to be explored. Figure 4.3 describes the national GDP and provincial agricultural production growth trends for the baseline scenario, highlighting the two provinces of Pakistan that consume the most water (Punjab and Sindh), while an aggregated representation is included for the rest of the country. In 2008, the baseline year, 63 percent of production comes from Punjab, 20 percent from Sindh, and 17 percent from the rest of Pakistan. Most of the production in Punjab and Sindh is irrigated by the Indus River basin, while agriculture is mostly rainfed in the rest of Pakistan. For the baseline scenario, we specify an economic growth rate of about 3 percent per year.[4] The amount of agricultural land does not increase, but its productivity grows, so less land is needed per unit of output over time. Under these assumptions, Sindh's agricultural production increases with its GDP because of improved yields, while Punjab's production increases in line with GDP until 2035 but slows thereafter due to pressures of rising industrial and domestic water demand on already stressed water supplies. Agricultural commodity prices increase in real terms by an average of about 30 percent when the last years of the simulation are reached.

The Diamer-Bhasha Dam. The Diamer-Bhasha Dam (often called the Bhasha Dam), on which construction officially started in 2011, is a large dam project situated in Gilgit-Baltistan on the Indus River, upstream of the Tarbela Dam. It will be 272 meters high and is projected to hold 8.1 MAF of water, including 6.4 MAF of live storage that can be delivered out of the reservoir. The associated hydropower station will have a total installed capacity of 4.5 gigawatts. As of 2011, the project's cost was estimated at US$13.6 billion, with completion expected in 12 years.

Although efforts to assess the costs and benefits of the Bhasha Dam have been controversial, there are clearly some significant advantages to this project. According to the Water and Power Development Authority (WAPDA),

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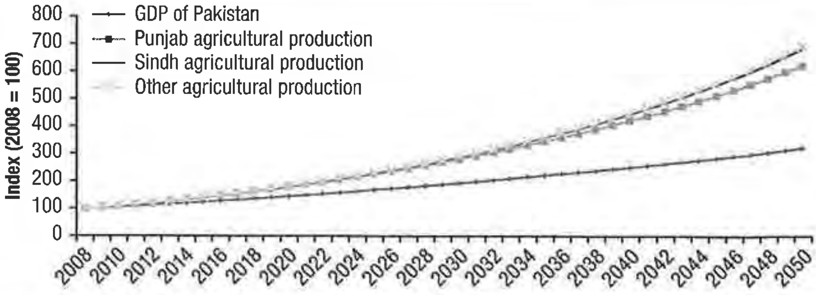
[4] The calibration of the growth rate is essentially done by specifying exogenous rates of total factor productivity growth. Labor force growth is also exogenous and includes some productivity increases in addition to the added supply, while growth of the capital stock is endogenous, determined by aggregate annual savings and investment.

FIGURE 4.3 Baseline projections of CGE-W of GDP and agricultural production by province, 2008–2050



Source: Authors, results from the CGE-W model.

Note: CGE-W = computable general equilibrium-water; GDP = gross domestic product.

which is in charge of building and operating the dam, the live storage is valued at US$0.63 billion annually for irrigation purposes and at US$2.2 billion for hydroelectricity generation, paying back construction costs in eight years.

Using the CGE-W framework, we reestimate GDP benefits and other dimensions while doing the following: (1) explicitly modeling the impact of the new capacity on irrigation water supply and hydropower, (2) accounting for both direct and indirect effects of improved agricultural production and increased energy production on the economy, and (3) considering climate change impacts on crop production and hydropower.

Figure 4.4 presents the GDP results for three different scenarios. In the first scenario, represented with a gray line with hash marks and labeled "Average with Bhasha," every year experiences the same weather as the average year (which means no dry or wet spells), assuming—for convenience in this modeling exercise—that the Diamer-Bhasha Dam came online in 2009.[5] In the first year of operation, GDP rises by 0.3 percent, mostly due to hydropower benefits. Agricultural benefits, on the other hand, remain flat until 2020, as water stress is not significant in the earlier years. These benefits rise to 0.55 percentage points above the baseline GDP by 2050.[6] Overall, the

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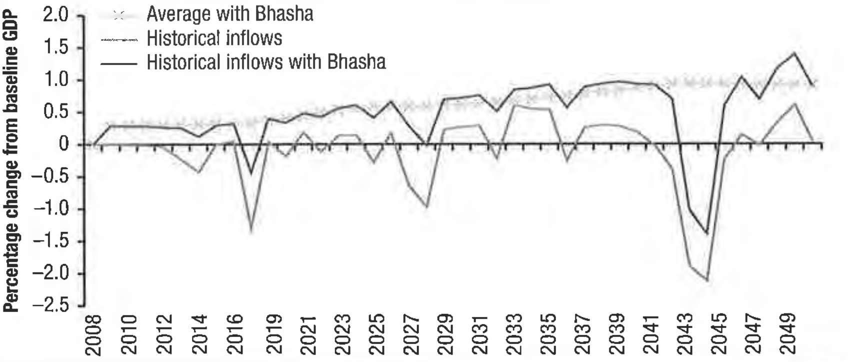
[5] Specifically, the model uses historical data and creates future scenarios from those data using 2008 as the base year and 2009 as the first year in the simulation.

[6] The results for scenarios run without hydropower benefits are not shown here.

FIGURE 4.4 Estimated change from baseline GDP with historical inflows and Bhasha Dam, 2008–2050



Source: Authors, based on results from the CGE-W model.

Note: CGE-W = computable general equilibrium-water; GDP = gross domestic product.

benefits go up to 0.9 percent above the baseline GDP by 2050.[7] Total agricultural production goes up by 2.6 percent in Punjab and 0.6 percent in Sindh. Punjab gets higher benefits from the dam in 2050, as under our baseline scenario it is the most water-stressed province. Conceptually, the dam helps Punjab alleviate increased water stress due to population and economic growth, while Sindh is somewhat protected by the 1991 Water Accords.

In the second scenario (shown by the dark gray line labeled "Historical inflows"), we introduce annual variability. To do so, we reproduce the time series of flows of the major rivers for the years 1966/1967–2007/2008. Droughts can create up to a 4 percent loss in GDP (in 2043 and 2044),[8] while a relatively wet year may increase GDP by about 1 percent (in 2033). Drought impacts can be seen even at the beginning of the period. Nonagricultural water demand is growing along with the economy, so a drought or a wet year in later years will have more impact on GDP than one in earlier years.

In the third scenario (the solid line labeled "Historical inflows with Bhasha"), the addition of the Diamer-Bhasha Dam improves GDP by approximately the same amount as in the first scenario under average weather. The

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[7] We do not take into account the cost of building the dam in this analysis. Conceptually, the dam appears on the Indus on the first day of the 2009 water year, which runs from April to March. The model as implemented here measures benefits but does not consider costs. Moreover, we do not consider dam silting, which is likely to reduce storage over time.

[8] Because we are mapping to historical years, the 2043/2044 drought corresponds to the historical 2001/2002 drought in Pakistan. The GDP shock we calculate here is in line with estimates from the State Bank of Pakistan (2002).

main difference is that it provides some insurance against droughts. For example, in 2014 the drought impact on agricultural production is reduced by three-quarters because of the addition of the Diamer-Bhasha Dam. During a drought, the dam can save as much as 2 percentage points of GDP because it protects agricultural production, and in wet years, it can add an extra 0.5 percentage point.

A Note on Price Behavior. In order to see the context of the simulations in this section and the next one, which also uses results from the CGE-W, and to gain an understanding of key assumptions behind the future scenarios, we look at prices. Price levels observed for selected years, relative to a baseline of 1.0 in 2008, provide a good initial window into those assumptions. Table 4.1 provides real prices in the historical simulation, which models historical water flows being repeated in the future but without Bhasha Dam being present, for 2029 and 2050. The first column gives the comparison in prices for commodities in 2029. The upper panel contains crops most affected by changes in water availability and that see only moderate price increases halfway through the projections. In this group, cotton, sugarcane, and horticultural crops see the highest price increases in 2029, as they are commodities with higher growth in demand from rising incomes.

The bottom part of the table, which covers commodities and sectors with fewer land or water constraints, shows that price increases in services, manufactures, and textiles tend to be smaller, despite anticipated growth in those sectors. In contrast, the crop-related products, including livestock and processed food, see fairly high price increases because of rising prices of raw materials and feed inputs, but also because of rising demand.

The picture changes substantially in 2050 as all prices for agricultural products (except livestock) rise, and some are 50 percent higher than 2008 prices in real terms. The staple products rise the fastest in the final 20 years of the projection, with wheat, sugarcane, and horticultural crops climbing between 30 and 40 percentage points. The highest water users among the agricultural products, cotton and rice, see the largest price gains, with basmati rice doubling and cotton rising by 60 percentage points. This scenario clearly shows the growing effect of a growing population and limited resources in agriculture, and the relative ease of expanding nonagricultural sectors, thereby keeping those prices lower as textiles, manufacturing, and services see little real price increases over the years.

Because real prices are rising, growth in demand must be exceeding supply. The two major factors are population on the demand side and productivity on the supply side. The overall growth in population was assumed initially to be

TABLE 4.1 Historical simulations of real price changes of crops and other commodities, 2029 and 2050

Crops	Price Level (2008 = 1) 2029	Price Level (2008 = 1) 2050
Water-sensitive crops		
Wheat	1.04	1.40
IRRI rice	1.01	1.43
Basmati rice	0.94	2.15
Cotton	1.13	1.73
Sugarcane	1.09	1.44
Horticultural crops	1.35	1.69
Other commodities/sectors		
Livestock	1.43	1.39
Processed food	1.37	1.44
Textiles	1.06	1.15
Manufactures	1.17	1.11
Services	1.03	0.94

Source: Authors, based on results from the CGE-W model.

Note: CGE-W = computable general equilibrium-water.

1.5 percent per year, and it declined over the simulations to zero in the last five years, thus implying a reduction in population growth rates. However, even with a declining annual rate of growth, population grows by 41 percent across the 42 years in the simulation, so the total population in 2050 reaches 233 million. (This is close to the low estimate of the United Nations. With a medium UN projection of 271 million and a high projection of 311 million people, our projections may underestimate demand growth and thus real price increases.)

The average total factor productivity growth was about 0.6 percent per year, or slightly less than 27 percent over the 42 years in the simulations. These rates did not vary significantly across sectors, so price differences are not due to productivity changes. Additionally, factor-specific technical change is assumed for the land, labor, and capital inputs, and runs from 0.5 percent to 1 percent per year for agricultural labor productivity. It is much higher, up to a maximum of 4 percent per year, for skilled labor and land. These assumptions relax the constraint on land otherwise imposed in all simulations. In general, these gains raise the productivity of land, so growth in output per unit of land increases substantially for most crops. In contrast, the actual growth in yields over the past 40 years has been less than 1.0 percent over the period 1969/1970–2010/2011 for most crops, and was highest in maize, at 3.2 percent. The actual cotton and wheat growth rates are half the simulated values of 2.2 percent and 2.1 percent, respectively. If we had used the actual yield increases, prices would rise more because of lower productivity growth, so it may well be that real prices could be higher due to both productivity and population reasons.

The pattern of imports and exports in the historical simulations, with and without Bhasha Dam, give further support to the perspectives above. Consistent with a higher demand for all goods and services, total imports rise by 5.1 percent per year in the historical simulations, with manufactured goods, business services, petroleum, mining, and chemical products being the largest imports in 2008 and 2050. A reduced supply of water to the wheat crop, discussed below, leads to higher wheat imports, with a 7 percent growth rate per year. This is likely because of rising water use in kharif, especially late in the season, from cotton, sugarcane, and basmati rice crops, and the lack of storage to provide water for the rabi season. Also, exports show a shift toward textiles, where that sector ends up with nearly 60 percent of total exports versus 45 percent in 2008. (The percentage for 2008 may be low, however, because of the worldwide financial crisis in that year. The reported textiles exports were 53 percent in 2013 and 55 percent of all exports in 2014 [GoP 2015]). This is also consistent with the rise in water use shown earlier for cotton. Cotton lint exports, however, decline, as the raw cotton lint is used for higher value-added processing into cloth.

Economic Dimensions of New Storage in the Face of Climate Change. Table 4.2 shows the effects of climate change on Pakistan's GDP and agricultural production under four climate change scenarios, which are presented as deviations from the historical baseline scenarios with and without Bhasha, which are given in Figure 4.4. Inflows are affected by changes in runoff in the Himalayas, along with variations in minor river inflows, runoff in Pakistan, and rainfall, while crop water requirements are adjusted to reflect changes in plant evapotranspiration and other transfers of water to the atmosphere.

All climate change scenarios produce similar negative impacts on Pakistan's water system, which are driven mostly by temperature change and increases in evapotranspiration. Climate impacts on irrigated agriculture cost Pakistan an average of between 0.5 and 1.2 percentage points of GDP annually by 2050, with a 0.7 percent to 1.3 percent annual decrease in agricultural production compared to the historical baseline and with Punjab and Sindh bearing roughly equal impacts. The Diamer-Bhasha Dam mitigates the impact on agricultural production until the 2030s in the MIROC A1B

TABLE 4.2 Average annual changes in GDP and agricultural production from climate change, with and without Bhasha Dam, 2010s to 2040s

	Average annual GDP change (%)			
Scenarios*	2010s	2020s	2030s	2040s
MIROC A1B	–0.10	–0.30	–0.44	–1.22
MIROC A1B with Bhasha	0.48	0.44	0.33	0.24
MIROC B1	–0.68	–0.21	–0.37	–0.65
MIROC B1 with Bhasha	0.49	0.49	0.40	0.48
CSIRO A1B	–0.05	–0.19	–0.35	–1.11
CSIRO A1B with Bhasha	0.50	0.49	0.40	0.37
CSIRO B1	–0.03	–0.11	–0.19	–0.45
CSIRO B1 with Bhasha	0.51	0.57	0.56	0.73
	Average annual change in agricultural production (%)			
MIROC A1B	–0.22	–0.98	–1.24	–1.01
MIROC A1B with Bhasha	0.37	0.34	–0.07	–0.24
MIROC B1	–0.07	–0.79	–1.06	–1.30
MIROC B1 with Bhasha	0.40	0.50	0.12	0.17
CSIRO A1B	–0.12	–0.62	–0.97	–0.73
CSIRO A1B with Bhasha	0.42	0.62	0.16	0.09
CSIRO B1	–0.06	–0.36	–0.57	–0.95
CSIRO B1 with Bhasha	0.44	0.91	0.62	0.68

Source: Authors, based on results from the CGE-W model.

Note: *Climate change is modeled using four different AR4 (Fourth Assessment Report) general circulation models: CSIRO and MIROC, A1B and B1. CSIRO is based on a model of Australia's Commonwealth Scientific and Industrial Research Organization (CSIRO), and MIROC is based on the Model for Interdisciplinary Research on Climate (MIROC), produced by the University of Tokyo's Center for Climate System Research (following the methodology of Jones and Thornton [2013]). The two CSIRO scenarios have smaller but more evenly distributed precipitation increases. The two MIROC scenarios have higher increases in precipitation but more variability.

scenario and until the 2050s in the other scenarios, as shown in Table 4.2. Moreover, because of hydropower benefits, the overall GDP of Pakistan remains higher with Diamer-Bhasha Dam in 2050 than it would be without climate change and without the dam.

Economic Valuation of Added Storage and Hydropower from the Diamer-Bhasha Dam. Standard measures used to evaluate large engineering projects include benefit-cost ratios (BCR) and internal rates of return (IRR). The analysis requires a comprehensive measure of the benefits of the project, including both direct and indirect benefits, the latter of which are usually hard to measure (Cestti and Malik 2012). The CGE-W helps to solve this problem by including a complete view of the country's economic conditions, which facilitates construction of counterfactuals that include all benefits.

Using the CGE-W system of models, we can compute the BCR and IRR of the Diamer-Bhasha Dam based on the change in GDP between scenarios with and without the dam. Under the baseline scenario (without weather variability or climate change), the BCR of Bhasha Dam is 2.8 percent and the IRR is 10.3 percent, while under historical weather variability, the BCR is 3.2 percent and the IRR is 11.1 percent.[9] The IRR and benefit-cost ratios of Diamer-Bhasha Dam also increase with climate change, with BCRs of 3.3 to 3.9 and IRR values from 11.3 percent to 13.9 percent.

Water Allocation Effects from Bhasha Dam and Climate Change Simulations. To provide more-detailed measures of performance than seen in the GDP variation, we examine the effects on water allocation to crops and provinces of different climate change scenarios. In all these climate change scenarios, Bhasha Dam is included and the effects are taken into account. We also examine income distribution effects, which are generally similar in direction though slightly different in magnitudes, under various scenarios in Annex C.

Figure 4.5 shows the total water allocated to crops as estimated by four simulations. The first is the historical simulation, which reflects the same scenario, without Bhasha, as shown in Figure 4.4. Figure 4.5 also shows simulations of water applied to crops with the addition of Bhasha Dam and for two climate change scenarios, MIROC A1B and CSIRO B1, both with Bhasha Dam included. These three simulations are used to capture differences in the models used and also to represent the upper and lower bounds from the GDP outcomes seen earlier.

All four simulations shown in Figure 4.5 experience approximately the same historical shocks, but the three that include Bhasha Dam shift upward relative to the historical simulation. They all have variable trends at or above 80 MAF until the last 15 years, when, after 2032, water supply to crops can decline to close to 75 MAF, depending on the scenario. The addition of Bhasha Dam adds 3–4 MAF relative to the historical simulation after the first 15 years, and the two climate change simulations, which include Bhasha, shift water supply further upward. The CSIRO B1 simulation rises about 1 MAF above Bhasha Dam alone during the last decade, while the MIROC A1B adds 1 MAF more of water supply above CSIRO B1. Thus, the construction of Bhasha Dam in the presence of climate change could raise available water for

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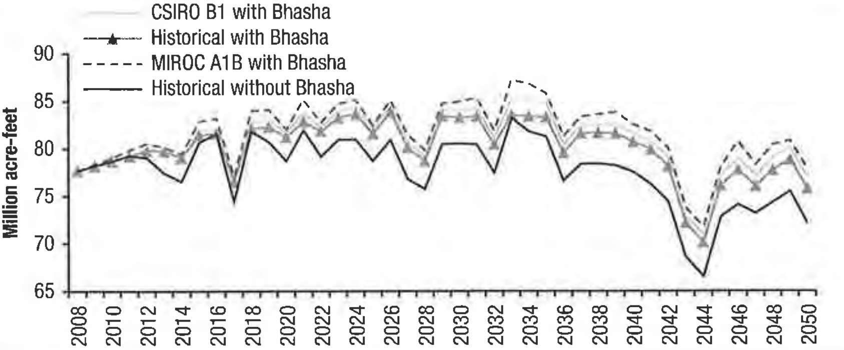
[9] We use a discount rate of 5 percent per year in the benefit-cost analysis.

FIGURE 4.5 Four simulations of total water supplied to crops, 2008–2050



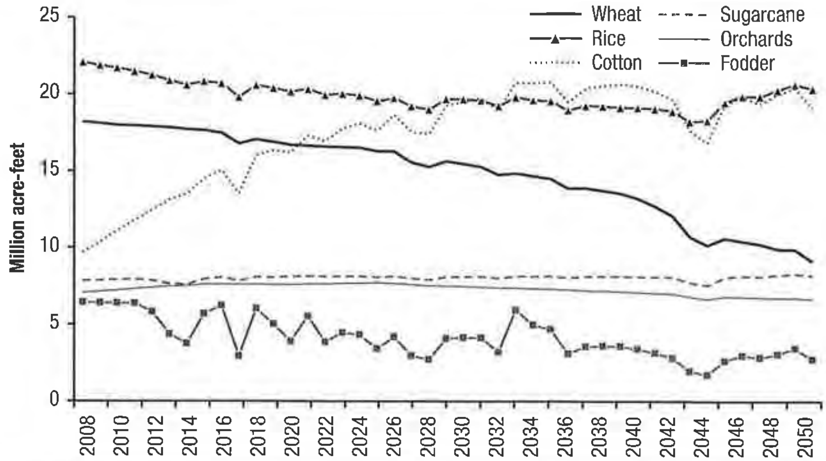
Source: Authors, based on results from the CGE-W model.
Note: CGE-W = computable general equilibrium-water.

agricultural purposes by nearly 5 MAF under the assumptions of each simulation, as described in the note to Table 4.2.

These changes can also be examined from the perspective of each province. For example, in MIROC A1B, which adds the most water to crops, Sindh, KPK, and the irrigated portion of Balochistan receive larger allocations: nearly 10, 24, and 32 percent more water applied to crops, respectively. The loss in water supply to crops seen in the later years of Figure 4.5 therefore comes from the Punjab, which loses 9.7 MAF, or nearly 15 percent of its allocation.

With changing overall water supply and other factors, such as population, income, and productivity, growing over time, water applied to crops changes during the historical simulation, as shown in Figure 4.6. The most dramatic change is a doubling of water applied to cotton. Water applied to wheat drops from 18 MAF to about 10 MAF, a reduction of nearly half. Water applied to fodder also declines, as does water applied to rice, but the latter recovers somewhat. Thus, the simulation shows that water availability in the presence of other forecasted changes is expected to cause significant shifts in water use by crop. These shifts will have indirect effects on several commodities. Textiles will have a much larger domestic source of a key input, cotton, but it is likely that the growth in demand for textiles is increasing the profitability of cotton production, so the cotton crop expands its water use dramatically. It might also be expected that livestock would decline because key sources of feed, fodder and wheat straw, decrease. However, as constructed in this model, livestock can use feed from a wide variety of crops, including cotton, so animals have access to adequate sources of feed. In fact, as shown in Table 4.1, livestock

FIGURE 4.6 Historical simulation of water supply by crop, without Bhasha, 2008–2050



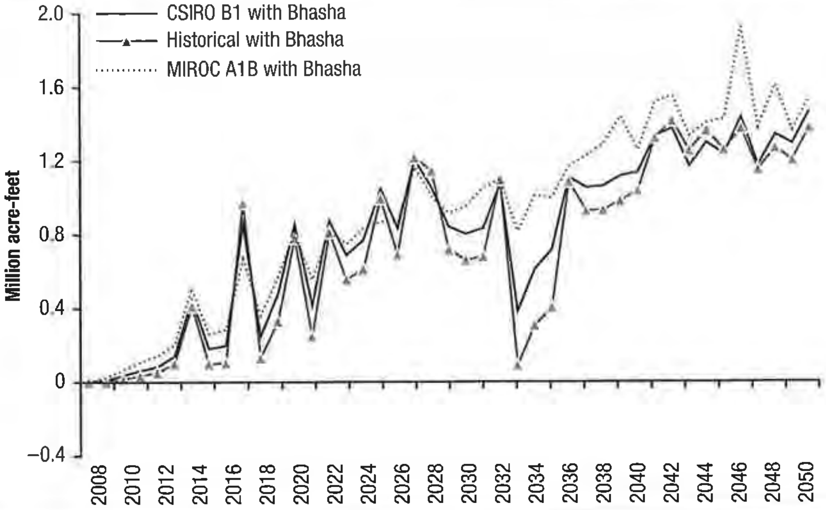
Source: Authors, based on results from the CGE-W model.
Note: CGE-W = computable general equilibrium-water.

prices actually decline somewhat, even though demand will clearly grow with higher incomes.

To illustrate the effects of climate change and new storage in the Bhasha Dam on particular crops, Figure 4.7 and 4.8 show how water application increases across the three scenarios for cotton and wheat, which are the two crops that see the largest effects. Cotton gains 1.5 MAF in all scenarios with Bhasha Dam added, in addition to the already high growth found in the historical scenario, and the fluctuations over time are similar across all simulations. In Figure 4.6, without Bhasha Dam, wheat experiences large drops in water supplies, but with Bhasha Dam included, all three simulations lead to a 1.2 MAF increase in applied water to that crop by 2050 (Figure 4.8).

In contrast, the fluctuations over time in the application of water to wheat vary. With just Bhasha Dam added, the amount of additional water grows slowly until the last decade of the simulation and then accelerates because of a combination of higher prices for staple products as demand rises, a roughly 3 percent increase in evaporation, and the availability of water storage, which makes water more readily available outside the rainy kharif season. In the two climate change simulations, however, more water is available for wheat because the major outcome of these scenarios is a shift to later in the year, for both inflows to the IBIS and rainfall. The October to December period, part of which falls in the historically drier rabi season, nevertheless sees an increase in inflows of 2 percent and

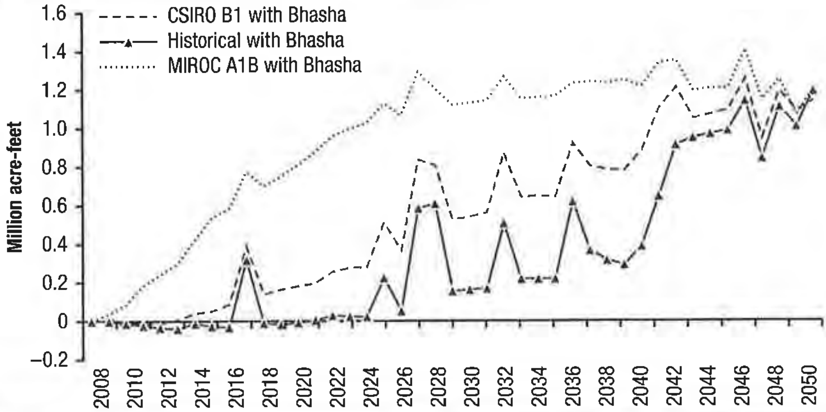
FIGURE 4.7 Changes from historical simulation of water supplied to cotton from climate change and Bhasha, 2008–2050



Source: Authors, based on results from the CGE-W model.

Note: This figure shows deviations from the historical simulation, which is without Bhasha Dam or climate change. CGE-W = computable general equilibrium-water.

FIGURE 4.8 Changes from historical simulation of water supplied to wheat from climate change and Bhasha, 2008–2050



Source: Authors, based on results from the CGE-W model.

Note: This figure shows deviations from the historical simulation, which is without Bhasha Dam or climate change. CGE-W = computable general equilibrium-water.

of rainfall of 4 percent relative to the baseline. Additionally, the overall increase from adding Bhasha Dam and the climate change scenarios shown in Figure 4.5 adds water over and above the seasonal shift.

Strategies to Increase Agricultural Productivity and Modernize Existing Irrigation Infrastructure

The previous section examines the economic effects of added storage of water with the addition of the Bhasha Dam. This section uses the CGE-W model to look at additional strategies to solve pressing water issues, including effects of measures suggested by Laghari, Vanham, and Rauch, "rehabilitation and modernization of existing infrastructure," "increasing water productivity in agriculture," and "economic instruments" (Laghari, Vanham, and Rauch 2012). We use both the CGE-W model and the stochastic frontier model that is described in the section below to gain insights into these areas. The CGE-W model is used particularly to investigate the following possible solutions to selected issues: watercourse efficiency, improved timing of water delivery, and permitting of water trading across provinces. This section focuses on GDP and water allocation, and Annex C discusses income distribution effects.

Watercourse Efficiency. This simulation examines the effects of improving efficiency in watercourses, which amounts to reducing losses in distribution. It does so by raising water distribution efficiency to 70 percent (compared to an average of 55 percent used in the baseline CGE-W model), which can come from watercourse and canal lining, or from better allocation via water user associations. This is a good example of the benefits of "rehabilitation and modernization of existing infrastructure." Indeed, the Punjab government has been undertaking major projects on watercourse lining for many years. Since 1981 the province has improved 14,252 watercourses, with the assistance of the World Bank, under the National Program for Improvement of Watercourses in Pakistan (Punjab Component), and it is planning to line 7,000 additional watercourses in the Punjab Irrigated Agriculture Productivity Improvement Project (PIPIP) (DG Agriculture 2011). This improvement in infrastructure leads to a greater availability of surface water, so our simulation increases the proportion of water that reaches the field. We call this simulation "watercourse efficiency" (WCE) to refer to the simulations that raise water distribution efficiency.

Improved Timing of Water Delivery. Improved timing of water delivery is a central focus in the econometric analysis, discussed in the following section "Economic Benefits from the Use of Groundwater and Surface Water in

Irrigation" and in Annex B, which identifies significant productivity gains from using groundwater at the farm level. The gains from better timing come through matching supply and demand for water more closely so that adequate water is available when crops have higher demand. Access to groundwater improves timing, but better timing also comes from the improved delivery described above, as seepage losses are reduced and the velocity of water through the watercourse is increased, thereby allowing farmers in lower reaches of the watercourse to irrigate more land in a given turn. This simulation, called TMG for "timing," captures this benefit by simulating direct gains in yields, at the level farmers get when they use sufficient, but also perfectly timed, groundwater. The econometric analysis shows an increase of 13 percent in the value of output as groundwater proportions increase, so this simulation adjusts the overall yield in various regions by this amount, depending on the proportion of surface water used, assuming that the groundwater portion is already leading to higher yields.

Permitting Water Trading across Provinces. The 1991 Water Accord creates relatively fixed allocations of water across provinces, so the third option we pursue is to examine the effect of reducing those restrictions so that trading among provinces can be pursued to create the highest economic benefit. In the simulation, called TRADE, different allocations are permitted depending on the volume of water in the Indus, and predicting these on a monthly basis in a model, taking into account both future and past dimensions, is difficult. Thus, meeting the requirements of the Water Accord is a soft rather than a hard constraint. The focus of the TRADE simulation is to see the effect of releasing the allocations specified under the Water Accord. It is an example of an "economic instruments" solution.

Figure 4.9 presents differences in each simulation compared to the historical scenario levels of overall GDP from 2008 until 2050; the simulations include the same productivity and population assumptions used for the earlier Bhasha Dam and climate change simulations. The figure presents the GDP outcomes from four individual simulations, including TMG, TRADE, and WCE as described above, with Bhasha Dam (called BDAM) added as a fourth individual simulation.[10] We also present the combined scenario that has the highest benefit, to provide an example of the benefits of multiple investments.

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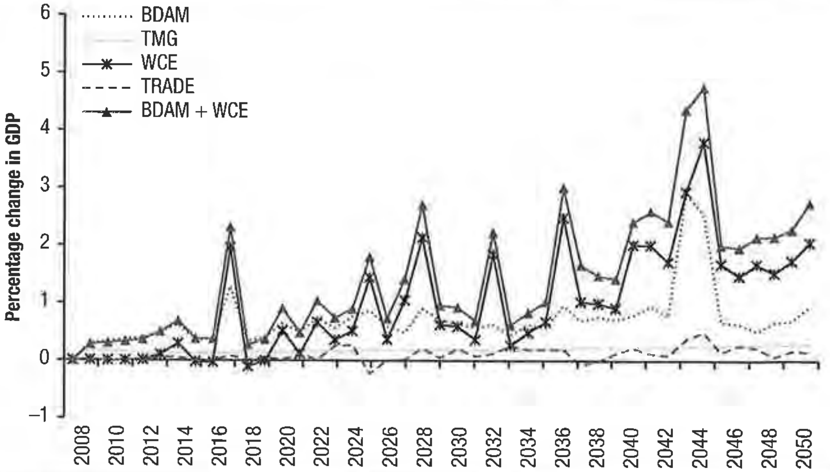
[10] This is the same simulation as the one presented in Figure 4.4 as "Historical inflows with Bhasha" to look at climate change effects, but is renamed to facilitate a comparison between the four different proposed solutions.

FIGURE 4.9 Changes in GDP from historical baseline from selected improvements in IBIS water management, 2008–2050



Source: Authors, based on results from CGE-W model.

Note: The simulations included are BDAM, adding Diamer-Bhasha Dam alone; TMG, better timing of water application; TRADE, relaxation of the 1991 Water Accord; and WCE, reduced seepage losses in water courses. The combined scenario with the highest impact BDAM + WCE is also included. This figure shows deviations from the historical simulation, which is without Bhasha Dam or climate change. GDP = gross domestic product. IBIS = Indus Basin Irrigation System.

Figure 4.9 shows that three improvements are most beneficial to GDP growth. The WCE simulation, which involves watercourse efficiency improvements, mainly through lining the watercourses, adds 2.0 percent to GDP over the historical simulation, and the BDAM scenario adds more than 1.0 percent by 2050. The best performer is the combined simulation of BDAM + WCE, which exceeds the historical simulation by 2.8 percent in 2050. The two other improvements considered, TRADE and TMG, add just 0.2 percent to GDP by 2050.

With scarce, and fixed, land and water resources serving the strong population growth and gains in real income, increased water supply provides growing benefits over time and helps reduce prices of key commodities relative to the baseline scenario (shown in Table 4.1). Because both BDAM and WCE add water, either through storage or reduced losses in distribution, they are the simulations that have the best performance. In the early years, BDAM benefits from growth in hydropower. However, with a fixed reservoir volume, that benefit does not continue to grow, and it ends up contributing only 1.0 percent to GDP by 2050, with half of the benefits from hydropower, while WCE contributes 2.0 percent to GDP. Because the combination of WCE and

BDAM adds water to crops in a complementary fashion, investing in both of them together gives the highest contribution to GDP.

Among the three simulations that add the most to GDP, one clear pattern in the results is the upward spikes in GDP only in years when the historical series by itself has downward shocks (these shocks are shown in Figure 4.4). These upward spikes occur because in Figure 4.9 the presentation is in terms of the difference between the historical series and a given simulation. Therefore, the existence of BDAM or WCE provides protection against the declining GDP in drought years, and that can be substantial at times. In the largest drought year, 2044, BDAM saves 2.6 percent in GDP, WCE saves 3.8 percent, and the two combined investments save 4.8 percent in GDP. The combination of BDAM + WCE appears to be above WCE alone by only 1 percent, and therefore some redundancy in water provision may be evident, as the benefits are not a simple addition of the two investments.

Stepping back for an overview, we see that among the individual runs, WCE clearly attains the highest GDP benefits. In fact, from a purely economic standpoint given the expense of constructing Bhasha Dam as in the BDAM scenario, WCE may be the best choice (and is being done via projects now). Therefore, the relative costs, and the political and institutional requirements, should be assessed closely to determine whether investing in large dams is beneficial, or whether capturing economic gains of infrastructure investment could best be done through enhancements in watercourse efficiency.[11]

Water Allocation Effects of Solutions to Modernize Infrastructure and Enhance Water Agricultural Productivity. The preceding section examined the GDP effects for the four policies/investments: BDAM, TMG, TRADE, and WCE. It also looked at variations in the amount of water applied to key crops in the historical simulation. This section presents changes in the amount of water applied across the four scenarios, first by province and then as comparisons with the historical scenario for the two crops most affected, wheat and cotton. These policies/investments relate to modernizing infrastructure, increasing water productivity in agriculture, and economic instruments—three approaches suggested in Laghari, Vanham, and Rauch (2012).

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[11] The scenarios reported here are considered separately and interact only moderately. For example, timing benefits are not modified if watercourse efficiency is improved, although lined watercourses actually improve timing through increased velocity. BDAM affects the whole IBIS and surely interacts with other elements. Also, the model does not account for groundwater perfectly, so WCE ignores changes in groundwater recharge, and its value may be overestimated.

Figure 4.10 shows the changing water allocations to crops in the Punjab and Sindh for the simulations examined (BDAM, TMG, TRADE, and WCE). While these simulations do not show changes as large as the earlier climate change simulations, some of them do produce significant effects.

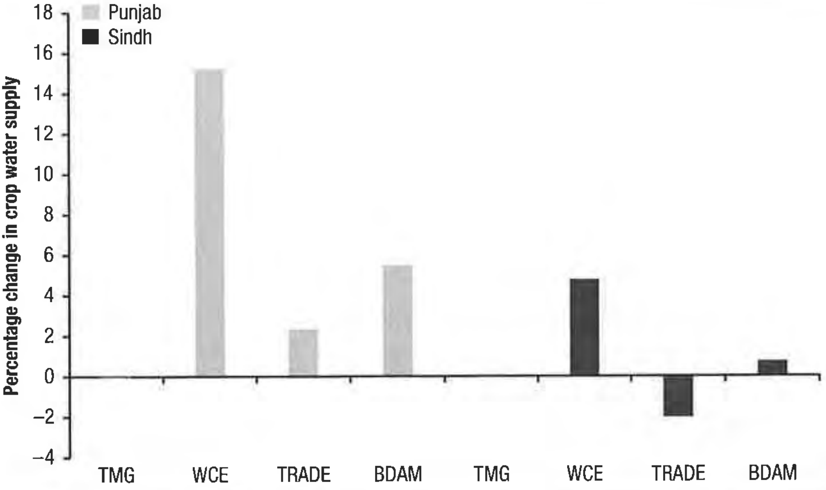
In the Punjab, the WCE simulation, showing a significant effect like that on GDP, raises the amount of water by over 15 percent; BDAM adds about 6 percent. WCE also has the greatest effect on the water applied to crops in the Sindh, increasing water supply by 4.8 percent. The likely explanation for WCE's greater effect relative to BDAM is that the large surface water system that exists in each province benefits from reduced losses in distribution and the fact that losses are reduced throughout the year, whereas BDAM tends to have a more concentrated seasonal effect. Compared to its contribution to GDP, TRADE has fairly significant effects on the amount of water applied to crops in both provinces, as it assists in moving supply to higher-valued uses: water is first directed to high-value uses in the Punjab before flowing downstream to the Sindh. Because TMG affects only yields, not water distribution, it has little impact.

In addition to looking at the impacts on water use by province, we examine how water consumption of key crops changes relative to the historical outcomes presented in Figure 4.6. That figure shows that water use is highest for rice and cotton, and the water used for cotton nearly doubles, from 10 MAF to 20 MAF, where it remains for the last 20 years of the simulation. Water use for wheat drops significantly from 18 MAF to about 10 MAF, a reduction by nearly half. Water use for fodder also declines, as does water applied to rice, but the latter recovers somewhat.

Figures 4.11 and 4.12 show how, compared to the amounts shown in Figure 4.6, water applied to cotton and wheat changes with various policies and investments. Figure 4.11 shows that compared to the historical simulation, cotton receives the most added water in the WCE individual simulation and the BDAM + WCE simulation. The WCE simulation provides increasing water throughout the years, rising to 6.2 MAF over the historical simulation. BDAM adds 2.0 MAF, and together WCE + BDAM add 7.7 MAF. The two simulations in general protect cotton production against the decline in overall allocations in the historical simulations (hence the spikes as in the GDP analysis in Figure 4.9), and WCE is particularly effective in that regard. The other alternatives do not play that role much at all. While the TRADE simulation has a small effect on water allocation, it does so opposite of WCE and BDAM, as it has the greatest contribution in allocating surpluses as opposed to maintaining water in times of drought.

Finally, water allocation to wheat, in Figure 4.12, in aggregate receives

FIGURE 4.10 Percentage change from historical baseline in crop water supply, Sindh and Punjab Provinces



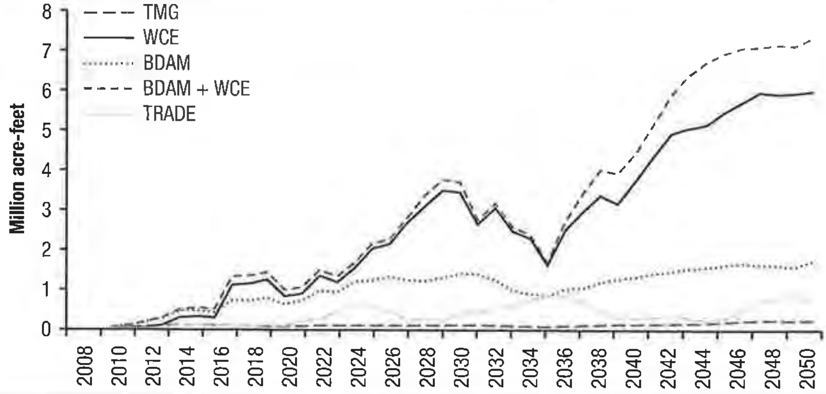
Source: Authors, based on results from CGE-W model.

Note: The simulations included are BDAM, Diamer-Bhasha Dam; TMG, better timing of water application; TRADE, relaxation of the 1991 Water Accord; and WCE, reduced seepage losses in watercourses. The changes are evaluated in the last year of the simulation, 2050.

significantly decreased allocations, and does not get much additional allocation in any simulations during most years. Prior to the last few years, the amounts are not large, rarely more than 200,000 acre-feet. However, as with cotton in the GDP analysis, the WCE and BDAM scenarios, individually and in combination, protect water for wheat in times of drought. The WCE value found in Figure 4.12 in 2044 is about 1.26 MAF, nearly twice that of BDAM. Together, the BDAM and WCE simulations retain 1.44 MAF of water in wheat production. These large spikes, as noted, are really protection afforded to wheat production in a major drought year, spikes that are at their highest when the drought is at its worst. That is, together, BDAM and WCE provide the most additional allocation of water to wheat in 2044, and TMG provides the least.

The section below finds further support for the WCE's value, as the econometric results demonstrate that a *khal panchayat* (water users' association) on a watercourse raises efficiency, as farmers with those institutions are 20 and 21 percent more efficient in kharif and rabi, respectively, than farmers without such institutions. However, many of the *khal panchayats* in Pakistan came about through an on-farm water management project that requires establishment of these institutions as a precondition for infrastructural improvements

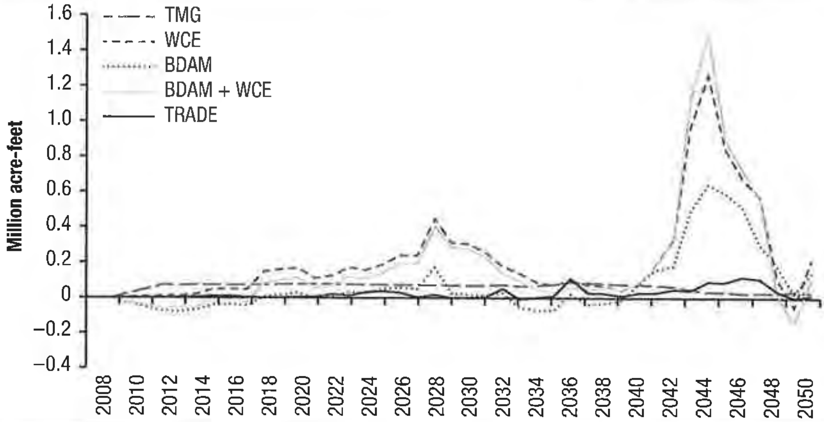
FIGURE 4.11 Change from historical simulation of water supplied to cotton from selected improvements in IBIS water management, 2008–2050



Source: Authors, based on results from CGE-W model.

Note: IBIS = Indus Basin Irrigation System. The simulations included BDAM, Diamer-Bhasha Dam; TMG, better timing of water application; TRADE, relaxation of the 1991 Water Accord; WCE, reduced seepage losses in watercourses; and BDAM + WCE, a combined scenario.

FIGURE 4.12 Changes from baseline simulation of water supply to wheat from selected improvements in IBIS water management, 2008–2050



Source: Authors, based on results from CGE-W model.

Note: IBIS = Indus Basin Irrigation System. The simulations included BDAM, Diamer-Bhasha Dam; TMG, better timing of water application; TRADE, relaxation of the 1991 Water Accord; WCE, reduced seepage losses in watercourses; and BDAM + WCE, a combined scenario.

such as canal lining (Mekonnen, Channa, and Ringler 2014; DG Agriculture 2011). Thus, the efficiency-enhancing effects of *khal panchayats* come from a functioning farmers' institution that maintains the watercourse over time, but these effects may also be a proxy for watercourse-lining development. There is thus consistency in the value of watercourse lining from both research approaches. However, the econometric work also suggests that the use of groundwater raises efficiency, which was interpreted as increasing yields from better timing (TMG) in the CGE-W analyses. This did not have the same effect in the whole-economy models as in the microeconomic analysis.

Economic Benefits from the Use of Groundwater and Surface Water in Irrigation

The rise of public sector SCARP tube well programs, designed to improve drainage after the expanded IBIS irrigation system led to increased water tables, is well documented in many water reviews (Basharat 2012; FoDP-WSTF 2012). One effect of this program was a vast increase in private wells, and overabstraction of groundwater became a serious problem in parts of the country, as about 40 percent of irrigation water is supplied by groundwater. However, farmers demonstrated a willingness to pay for electricity and to rent water, thereby showing the value of on-demand water availability, but sometimes implying a lack of other options (Davies 2012; Shah et al. 2009).

Issues also arise with the interaction of groundwater and surface water. Farmers at the head, or beginning, of a watercourse often use more water than optimal, leading to shortages downstream and more salinity in the tail, or the end, of the watercourse and thereby forcing farmers at the tail to depend more on groundwater. If the surface water system could be managed to match the accessibility of groundwater, and incentives could be in place to use water at optimal levels, significant systemwide benefits could result. This section gives a sense of the value of groundwater, and of the costs and benefits of location on a watercourse.

First, we analyze data from the RHPS Round 1.5, which indicates that groundwater use in Pakistan is prevalent, particularly in Punjab and KPK Provinces (IFPRI/IDS 2012). Nine out of 10 farmers in Punjab and 7 out of 10 farmers in KPK use groundwater for irrigation purposes (Table 4.3). Groundwater use is not significant in Sindh because the province faces salinity problems (Lashari et al. 2013), but 2 out of 10 farmers in Sindh still use groundwater for agricultural production. The majority of farmers who use groundwater in Sindh and KPK do not have access to surface water, while

TABLE 4.3 Households' use of groundwater and surface water by province, in kharif 2011 and rabi 2011/2012

Households' type of water use	Punjab	Sindh	KPK	Total
Canal water in kharif 2011 and rabi 2011/2012 (%)	0.685	0.820	0.431	0.718
Groundwater in kharif 2011 and rabi 2011/2012 (%)	0.890	0.190	0.706	0.629
Groundwater in kharif 2011 and rabi 2011/2012 (%)	0.315	0.174	0.569	0.280
Canal water in kharif 2011 and rabi 2011/2012 (%)	0.110	0.803	0.294	0.368
Both canal and groundwater in kharif 2011 and rabi 2011/2012 (%)	0.575	0.016	0.137	0.350
Observations	499	305	51	855

Source: Authors, based on data from RHPS (IFPRI/IDS 2012).

Note: KPK = Khyber Pakhtunkhwa.

58 percent of farmers in Punjab use groundwater in conjunction with canal water. Our survey shows that KPK relies heavily on groundwater, with 57 percent of farmers using only groundwater for irrigation. In contrast, more than 80 percent of farmers in Sindh use only canal water. Thus, policy instruments to either encourage or discourage groundwater use should take into consideration differences in the reliance of farmers on water resources across provinces.

Water productivity in agriculture is often tied to the types of irrigation methods practiced by farmers, and research on ways to encourage high-efficiency irrigation techniques is of great interest. Improvements in irrigation methods are the focus of major projects such as the new PIPIP, assisted by the World Bank, which started in 2011/2012 and intends to put 120,000 acres under drip irrigation (DG Agriculture 2011). The RHPS Round 1.5 shows that these newer methods are rarely used, as flood irrigation is predominant for both surface water and groundwater users, accounting for 82 percent of users in Punjab, 77 percent in Sindh, and 60 percent in KPK (Table 4.4). Furrows are used by many farmers, mainly in KPK, but the bed and furrow irrigation method is rarely used. The predominance of flood irrigation is surprising given the costs of groundwater, which would seem to encourage more water conservation, and that predominance limits efforts to improve agricultural water productivity.

Moreover, our survey data also give insights into the extent of exchanges of groundwater. On about 57 percent of plots, households indicated that they purchased groundwater from someone else on the watercourse, but simultaneously less than 2 percent of households said that they sold groundwater (Table 4.5). These responses could perhaps indicate the presence of a few

TABLE 4.4 Types of irrigation methods for surface water and groundwater by province, 2011/2012

	Punjab		Sindh		Khyber Pakhtunkhwa		Total	
Type	Number of plots	(%)	Number of plots	(%)	Number of plots	(%)	Number of plots	(%)
Flood	1016	81.80	456	77.29	91	60.26	1563	78.82
Furrow	202	16.26	70	11.86	47	31.13	319	16.09
Bed and furrow	24	1.93	64	10.85	13	8.61	101	5.09
Total	1242	100.00	590	100.00	151	100.00	1983	100.00

Source: Authors, based on data from RHPS (IFPRI/IDS 2012).

Note: Plot is the unit of observation in this table.

TABLE 4.5 Depth of wells and households' groundwater exchanges by province, 2011/2012

	Punjab	Sindh	KPK	Total
Depth of well (feet)	128.3 (91.99)	211.4 (133.3)	112.7 (64.83)	131.7 (94.99)
Households that sold groundwater to someone on the watercourse (%)	0.0132 (0.114)	0 (0)	0.0495 (0.218)	0.0154 (0.123)
Households that used groundwater that they purchased from a seller on the watercourse (%)	0.552 (0.498)	0.571 (0.498)	0.752 (0.434)	0.569 (0.495)
Observations	1,066	70	101	1,237

Source: Authors, based on data from RHPS (IFPRI/IDS 2012).

Note: Standard deviations are in parentheses. KPK = Khyber Pakhtunkhwa.

large tube well owners who sold groundwater to a number of other neighboring farmers. The responses could also mean information is being withheld, for a variety of reasons. Nonetheless, this kind of water marketing, although at a local level, is extensive, and is a type of economic instrument that should be promoted, perhaps through legislation that officially encourages this activity.

Econometric Analysis of the Impacts of Groundwater and Surface Water Use. To further investigate the relationship between groundwater and surface water, we estimate a frontier production function for irrigated agriculture in Pakistan and examine factors that determine the level of technical efficiency. This section emphasizes the conjunctive use and related issues; important insights from this analysis are examined in the following section.

The production function relates the value of output per unit of land, logarithmically transformed, to a set of production inputs: fertilizer, capital, pesticide, labor, volume of irrigation water (surface and groundwater are considered separately), and interactions of variables.[12] Additionally, there is an error term that is composed of statistical noise and production inefficiency, which permits an examination of the technical inefficiency of production by measuring the percentage of output lost due to inefficiency. In essence, this measurement describes how far a given observation is from the frontier, or the maximum production that can be obtained. The variables that influence the extent of inefficiency are included in the estimation to show what causes inefficiency, where the estimation is for kharif and rabi seasons separately.

We use the RHPS data described earlier to examine the nature of water use for the analysis of technical efficiency (IFPRI/IDS 2012). Given the large number of crops grown by households, we focus on the two major crops in rabi (wheat and berseem) and five crops in kharif (rice, cotton, sugarcane, sorghum, and millet), and control for these differences in the estimation. These crops account for more than 90 percent of harvested land in their respective seasons. For the purposes of this chapter, the two important variables included in the production function (*not* in the technical efficiency analysis) are groundwater and surface water use, which are specified as total inches used from each irrigation source in each season. The only significant variable (and only at 10 percent) was the total inches of groundwater used in rabi, and it was negative. Thus, based on these results, it appears that water use is not a key problem.

However, this effect varies across levels, and is positive and significant at reasonable levels. To show this outcome, Figure 4.13 depicts the elasticity of the value of output per acre for different levels of groundwater use in the sample. The results indicate that the responsiveness of output to groundwater is negative when groundwater use is greater than 2.7 inches (which is high compared to the average of 2 inches used in the sample), but it is positive at lower levels of use. A related analysis shows that the value of output per acre drops for those households that exclusively rely on groundwater and hence are most likely to overdraw the resource. Part of the reason seems to be that higher levels of groundwater use is associated with higher levels of groundwater depth, where groundwater tends to be more saline and thus affects the value of output.

Evaluation of Conjunctive Use Effects on Technical Efficiency. The stochastic frontier model jointly estimates a production function and an inefficiency effects model to capture the determinants of technical inefficiency of production. The inefficiency effects model permits an assessment of factors

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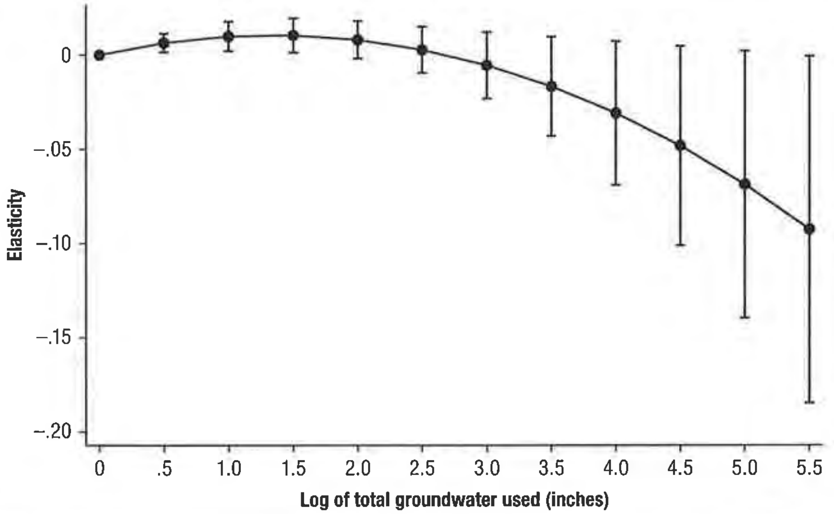
[12] The econometric results are provided in Annex B, which gives the full results from the stochastic frontier production function and the estimates of technical inefficiency.

FIGURE 4.13 Elasticity of values of output per acre in kharif with increasing groundwater use



Source: Authors' calculations.
Note: Values are presented with 95 percent confidence interval.

that affect efficiency levels, after differences in the use of inputs are accounted for in the production function. Based on this analysis, the mean technical efficiency score for irrigated agriculture in Pakistan in rabi is about 75 percent. Thus, there is a potential to increase output per acre by one-third (because of the calculation [100 – 75] / 75) through improved management of existing use of inputs. In the kharif season, the mean technical efficiency score is about 47 percent, implying an even greater potential gain from efficiency improvements than in rabi.

The technical efficiency of irrigated agriculture also varies significantly across the three provinces by season. During kharif, Sindh is more efficient than KPK and Punjab. Punjab is more productive, in the sense that it has a higher output per acre, but once the level of input use is taken into consideration, Sindh appears to be more efficient than Punjab or KPK in kharif (see the upper panel of Table B4.2 in Annex B). In rabi, the efficiency differential among the three provinces is not statistically different from zero.

The marginal effects on technical inefficiency for variables that are statistically significant in at least one season are presented in Table 4.6. The table shows the extent to which the variables have effects on the reduction of inefficiency, and the direction of that effect. Most of the terms are related to water

TABLE 4.6 Marginal effects of inefficiency-explaining variables on the mean of technical inefficiency by season

	Kharif		Rabi	
Explanatory variables	Mean	Standard deviation	Mean	Standard deviation
Ratio of groundwater to total irrigation water	–0.319	(0.154)	0.190	(0.105)
Rainfall was available on the plot	–0.275	(0.133)	0.0306	(0.0169)
Sindh[a]	–0.889	(0.430)	–0.0886	(0.0488)
Located at the head of the watercourse[b]	–0.182	(0.0880)	0.0673	(0.0371)
Located at the tail of the watercourse[b]	0.116	(0.0559)	0.100	(0.0552)
Household did not sell any crops in season	–0.0637	(0.0308)	0.0986	(0.0544)
Rented-in plots[c]	0.0514	(0.0249)	–0.0165	(0.00911)
Sharecropped-in plots[c]	0.258	(0.125)	0.0688	(0.0379)
Slightly sloped land[d]	–0.265	(0.128)	–0.0270	(0.0149)
Sandy soil[e]	0.169	(0.0818)	0.152	(0.0838)
Sandy loam soil[e]	0.00901	(0.00435)	0.124	(0.0682)
Average length of an irrigation turn (minutes)	0.124	(0.0598)	–0.0827	(0.0456)
Distance of plot from homestead	0.0328	(0.0159)	0.00343	(0.00189)
Flood irrigation used	0.217	(0.105)	–0.117	(0.0643)
Khal panchayat exist on the watercourse	–0.198	(0.0956)	–0.208	(0.115)
Log of age of household head	0.0928	(0.0448)	0.0644	(0.0355)
Plots experience waterlogging	0.269	(0.130)	–0.0697	(0.0385)
Producing sorghum only in kharif[f]	0.519	(0.251)	n.a.	n.a.
Producing cotton only in kharif[f]	0.553	(0.267)	n.a.	n.a.
Producing cotton and sorghum in kharif[f]	0.497	(0.240)	n.a.	n.a.
Producing only wheat[g]			–0.115	(0.121)
Observations	583		618	

Source: Authors' calculation using data from the RHPS (IFPRI/IDS 2012).

Note: *Khal panchayat* = water users' association. Marginal effects on mean inefficiency score are reported for variables that are statistically significant in at least one season as shown in the lower panel of Table B4.2. A negative sign indicates that the variable reduces inefficiency if its value rises. n.a. = not available.

[a] The base group is Punjab.

[b] The base group is households located at the middle of the watercourse.

[c] The base group of tenancy is privately owned plots.

[d] Base group is moderately sloped land.

[e] The base group is clay soil.

[f] The base group is producing only rice in kharif.

[g] The base group is producing both wheat and berseem in rabi.

issues in one form or another. First, the relative reliance on groundwater as a source of irrigation water has different impacts in rabi and kharif seasons. Farmers with a higher reliance on groundwater manage to get a higher output per acre in kharif, but not in rabi. This outcome may arise from the greater shortage of water in kharif relative to crop water requirements (though more water is available in kharif than in rabi, main kharif crops that consume more water such as rice and sugarcane may imply water shortages relative to crop water requirements in the season), so a farmer accessing more groundwater can better match supply and demand in that season. As Table 4.6 implies, increasing the ratio of groundwater use to 0.3, from its current level of 0.2, leads to a 3.2 percent reduction in technical inefficiency in kharif, thus increasing technical efficiency in that season from 47 percent to 50 percent, after controlling for the inches of groundwater and surface water used in the underlying production function estimation.

If all irrigation water comes from groundwater, assuming the marginal effect remains the same, technical inefficiency would drop by almost one-fourth, from 53 percent to 40 percent, or an increase in efficiency from 47 to 60 percent, a 13 percentage point efficiency gain. As a result, the value of output per acre could increase by about 13 percent. In practice, this means that surface water needs to be made as responsive as groundwater because current utilization of groundwater is felt to be at a maximum, or even excessive (Qureshi 2011). Also, this computation ignores some complications from increased use of groundwater, such as changes in quality, energy use, overabstraction and other environmental concerns that arise as more groundwater is brought into use. Despite its simplicity, however, it shows, at least regarding the current share of groundwater use, the possible benefit of improving accessibility and reliability of surface water to approach that of groundwater. The alternative of just using more groundwater is not an option in the IBIS, because there is already evidence of groundwater reaching the maximum level of abstraction.

The analysis also sheds light on conjunctive-use issues related to location on the watercourse. Farmers located in the middle of a watercourse are more efficient than tail-enders, in both kharif and rabi seasons. As shown in Table 4.6, this translates into a 12 percent efficiency differential between tail-enders and those located in the middle of the watercourse. The efficiency comparison between head-enders and those located in the middle varies by season. In kharif, where there are more limited water resources relative to crop water requirements, head-enders are 18 percent more efficient than those located in the middle, but this efficiency differential vanishes during rabi, when those in the middle are more efficient. The fact that in rabi, head-end water users lose efficiency to farmers located in the middle seems to support an oft-repeated point that in a *warabandi* system, overwatering occurs at the head of a watercourse—as happens to head-enders in rabi in this sample.

An important perspective on the evaluation of technical efficiency is whether farms have the discretion to alter the variables being examined or not. Clearly, farmers have a choice about how much groundwater to use and thus can affect the level of technical efficiency in that way. (This decision is then endogenous to the level of efficiency estimated.) In contrast, the location on the watercourse is not easily changed and might be thought of as a control variable that affects the level of inefficiency but cannot be part of a decision by farmers. However, from the perspective of groups of farmers on a watercourse, there is considerable opportunity to change performance related to locations along the watercourse.

The technical efficiency results shed light on other solutions proposed for the IBIS. One is land use planning and soil conservation, because the results show that farmers cultivating slightly sloped plots are 27 percent more technically efficient than those with moderately sloped plots in kharif. Farmers on slightly sloped land presumably have a more even distribution of water and achieve better water productivity and higher output. Also, farmers on sandy soils or sandy-loam soils are less efficient during the rabi season. Water leaves the root zone more quickly with sandy soils, so insufficient moisture is retained for crop use. Programs that enhance organic matter in the soil, and hold more water on the root zone, should aid water productivity.

There were also some puzzling outcomes. The average length of an irrigation turn has different impacts in rabi and kharif; increasing its length improves efficiency in rabi but does the opposite in kharif. This may be related to a higher water shortage in rabi, so that longer turns decrease the shortage, while it points to overwatering in kharif, a possibility with higher water velocities during that season. These outcomes are consistent with the flood irrigation results, which also have the unexpected result of increasing efficiency in rabi but leading to a decline, as expected, in kharif. This may again point to a relatively higher water shortage in rabi. Part of the issue at the head of the watercourse may be waterlogging from overuse of water, which is found to significantly reduce technical efficiency of farmers in kharif, because plots that are waterlogged are nearly 27 percent less efficient (Table 4.6). However, waterlogging in rabi is associated with better efficiency, again pointing to the shortage in that season. Thus, all three of these differing views on seasonal water shortages give a similar conclusion.

Finally, groundwater aquifers can be thought of as a large reservoir, so our analyses indirectly extend to the benefits of enhancing artificial groundwater recharge Laghari, Vanham, and Rauch (2012); Qureshi (2011). There may be situations when this approach is more advantageous and cost effective than using conventional storage options.

Conclusions

This chapter focuses on the economic dimensions of five possible solutions to issues in water resources. Using a microeconomic-level analysis and an aggregate, whole-economy approach (the CGE-W model), we examine five solutions in depth: reservoir management; coordinated management of surface water and groundwater; rehabilitation and modernization of existing infrastructure; increased water productivity for agriculture; and water trading in excess of the 1991 Water Accord. The analyses permit us to look at proposed solutions to challenges in the IBIS—solutions with more economic content than those contained in the literature to date.

The chapter assesses five solutions first in regard to economic benefits from possible improvements in each area. Assessments are made either by looking at GDP or the impacts on the value of agricultural production. The analysis shows that climate change reduces GDP at an annual rate between 0.5 percent and 1.2 percent by 2050, and causes an annual 0.7 percent to 1.3 percent decrease in agricultural production. To counteract this, the chapter examines large storage additions by simulating the effects of the proposed Diamer-Bhasha Dam. Our cost-benefit analyses in this case show that the IRR and BCR of Diamer-Bhasha Dam increase with climate change, with IRR calculations from 11.3 percent to 13.9 percent and BCR of 3.3 to 3.9. Expanded reservoir capacity therefore appears to be economically viable. However, this type of infrastructure contributes less over time because of its fixed water and energy contributions.

The chapter also uses the CGE-W model to examine three additional topics: rehabilitation and modernization of existing infrastructure, increased water productivity for agriculture, and water trading. The infrastructure analysis simulates the impacts of watercourse lining, which reduces losses in distribution; such development of watercourse lining is currently a major project in Pakistan. Agricultural productivity analysis looks at the effects of yield improvements from better timing of surface water deliveries. (We include Bhasha Dam for comparison purposes.) Of the options considered, watercourse lining, a type of improved infrastructure, is clearly the best option. It yields a nearly 2 percent gain in GDP by 2050 and provides protection against drought by making more water available in those years. For example, adding lining helps retain 6 MAF of water in cotton production and nearly 1.3 MAF in wheat production in years of drought. Putting Diamer-Bhasha Dam in place adds similar protection, but with smaller effects in all cases. The combination of these two investments always produces the largest effects, although the contribution of added storage via Bhasha Dam was smaller than watercourse lining. The other two investments evaluated, water trading and improved efficiency in matching water supply and demand, produce quite small effects.

Some important conclusions came from the review of water supply changes to crops across the various scenarios. The most dramatic change is that the water applied to cotton nearly doubles, which forces a decline in water applied to wheat, from 18 MAF to about 10 MAF. In a simulation with the presence of climate change and Bhasha Dam, cotton gains 1.5 MAF in applied water in addition to the already high application growth in the historical scenario, while wheat gains 1.2 MAF in water applied to partially offset the large decline in its share of irrigation water. Cotton receives added water in all simulations, but the amount is greatest in the lining and storage simulations. Rice, in contrast, gets reduced amounts of water in most simulations.

The analysis of the value of groundwater, and its interaction with the surface water system, is based on a frontier production function, using mainly an evaluation of technical efficiency. The benefits of using groundwater are substantial. If all irrigation water came from groundwater, technical inefficiency in crop production would drop by almost one-fourth, from 53 percent to 40 percent, and the value of output per acre could increase by about 13 percent. In practice, this means that given that current groundwater utilization is at a maximum, surface water needs to be made as responsive as groundwater. (This does not, however, appear to be that important in the CGE-W analysis.) Moreover, it is useful to think of groundwater aquifers as reservoirs and compare costs and benefits of management of that resource with more traditional storage facilities.

Two conclusions have major implications for areas of further research and more in-depth analysis. Storage clearly provides valuable economic benefits, and large storage, such as Bhasha Dam, provides a measure of insurance against the adverse effects of climate change. However, given that watercourse lining achieves many of the same objectives, probably with less investment costs and noting that half of the benefits from storage come from electricity, other combinations might make sense. Thus, it is possible that a combination of complementary investments, such as run of the river hydropower projects, which generate electricity from energy in river flows and not from stored water, watercourse lining, and more aggressive management of aquifers might achieve the same levels of benefits shown in this chapter.

Finally, the modeling results, based on maximization of total economic benefit, shows an increased allocation of water to cotton, less water to wheat, and correspondingly an increase in cotton production and a decrease in wheat production. However, food security is highly dependent on wheat as the major staple crop, and it is likely that small, food-insecure producers will continue to produce that crop, but at a disadvantage with less water. Therefore, based on this research, it may be that one of the best ways to improve food security could come from raising the water productivity in cotton production, which would allow water to be stored and carried into rabi for wheat production. This strategy might have a greater impact than one that approaches food security within wheat issues alone.

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Annex A: The Computable General Equilibrium–Water Model for Pakistan

In a country like Pakistan that is arid and relies heavily on irrigated agriculture (Briscoe and Qamar 2005), the water system is much more complex than can be considered by economic models that incorporate water in a simple manner. Water basin models that include some economic production track the direct effects of changes in the water system on only part of the economy and fail to encompass the direct and indirect repercussions on the broader economy, which are likely to be important in economies that are heavily dependent on water such as Pakistan. We need to integrate our knowledge of the entire economic system and its links to water systems to consider the challenges posed by climate change and potential adaptation strategies that involve a significant share of overall economic activity.

Our goal was to develop a model system that links economic and water models, drawing on the strengths of both approaches. This section presents such a model, the computable general equilibrium–water (CGE-W) simulation model applied to Pakistan. The economic model is a national CGE model adapted to link with a suite of water models that include hydrology, water demand, water basin management, and water stress, which are described in detail in Robinson and Gueneau (2014). Additionally, there is a hydropower module that calculates the electricity generated. It provides a flexible and robust framework for linking and integrating separate economic and water models.

The CGE-W Framework Applied to Pakistan

The CGE-W model of Pakistan consists of a national computable general equilibrium (CGE) simulation model that interfaces with a set of different water models: a water demand module, which translates economic values from the CGE into physical quantities of demand for water; a water basin management model (the Regional Water System Model for Pakistan [RWSM-Pak]), which optimizes water distribution over months and regions, and calculates related water shortages; and an associated water allocation model that allocates available water to crops based on the impact of water stress on crop yields and crop values (called the water allocation and stress model, or WASM). The water models all run on a monthly time increment. This set of models are linked together during each simulation. Outside of this set of interactions, a separate hydrology model calculates monthly precipitation and runoff to the river systems, given different climate scenarios, while another outside simulation, the hydropower model, calculates the electricity generated from water flows, which vary with the different climate change scenarios. All component models in this implementation of the CGE-W framework are coded in the General Algebraic Model System, which allows for integrated solution of the suite of models. Figure A4.1 presents a schematic view of how the system of simulation models operates year by year.[13]

The CGE-W model is solved dynamically (Figure A4.1). First, the CGE model is solved for a given year, assuming exogenous trends on various parameters. Solving the model yields projected outputs by sector and allocation of land to crops. The assumption behind this first run is that the expected water stress is set to the average of the previous three years, which sets harvest expectations for the allocation of land to different crops. The water demand module then calculates physical water demand for crops, industry, households, and livestock. Crop demand is calculated for each crop using evapotranspiration and effective rainfall; industrial water demand is assumed to be related to the square root of industrial GDP; livestock demand is the square root of livestock GDP; and household demand is calculated linearly to aggregate household income. RWSM-Pak uses these water demands, along with river flows provided by a hydrology model (or historical data) and climate parameters, to provide the monthly repartition of water among crops and regions given the objective function described above.

The water allocation and stress module (WASM) then allocates water among crops in an area, given the economic value of the crop. We use the FAO Ky approach (Doorenbos and Kassam 1979) to measure water stress using a multiplicative approach to include seasonality of water stress impacts (Jensen 1968; Hanks 1974; Raes et al. 2006). Because optimizing the total value of production given fixed prices leads to a tendency to specialize in high-value crops, we include a measure of risk aversion for farmers in the objective function, which preserves a diversified production structure even in case of a drought. The stress model produces a measure of yield stress for every crop—both irrigated and rainfed—in each of the twelve agroecological zones, which is then aggregated to the provincial level to match the regions in the CGE model.

Finally, the new yield shocks are calculated and applied to the CGE model, which is solved a second time for the final equilibrium, but the allocation of land to crops is assumed to be fixed because farmers cannot change their

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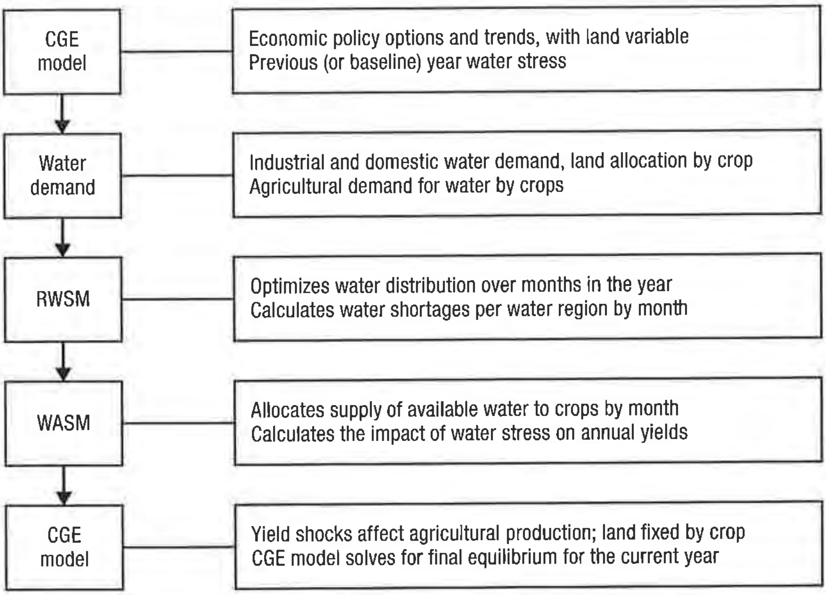
[13] Robinson and Gueneau (2013) describe the CGE-W framework in detail.

FIGURE A4.1 The CGE-W framework: Operation of the system of models in a given year



Source: Authors.

Note: CGE = Computable General Equilibrium; RWSM = Regional Water System Model; WASM = water allocation and stress module.

cropping decisions after planting. This solution yields all economic variables, including quantities and prices of outputs and inputs and all income flows. We then move to the next year, update various parameters on trends, and start the process again.

The IFPRI Standard CGE Model of Pakistan

The database for the IFPRI CGE model of Pakistan is based on a social accounting matrix (SAM) developed by Dorosh, Niazi, and Nazli (2006) and updated by Debowicz et al. (2012). The CGE model includes agricultural detail that allows for a good representation of water shocks on the economy, as well as disaggregated labor and household categories, to capture the distributional impacts of different policy choices. The SAM includes 45 sectors (or activities), 27 factors of production, and 18 household groups, allowing tracing of direct and indirect effects of potential scenarios through production and consumption linkages, including distributional effects. The model code starts from a new version of the IFPRI standard CGE model (Löfgren, Harris, and Robinson 2001).

The shock caused by water stress is defined as the ratio of crop yields for the current year compared to the baseline year yield. The baseline year data define the equilibrium of the water system in 2007/2008 under an average weather pattern. In the first run of the CGE model in each year, the external water shock anticipated by farmers is assumed to be the average of the four previous years, so farmers anticipate a short-term moving average level of water stress that allows for some adaptation. The CGE model then solves for the allocation of crops to irrigated and rainfed land based on these expectations.

The Regional Water System Model for Pakistan

RWSM-Pak is a water basin management model, but it does not include any economic measures because the economic links are handled in the CGE model. The basin management model covers only the Indus basin, which represents more than 90 percent of agricultural production in Pakistan. It is largely inspired by the original Indus Basin Model Revised (Ahmad, Brooke, and Kutcher 1990; recently updated by Yu et al. 2013). It models the nine main rivers of the Indus River basin that flow through Pakistan and provide irrigation water: from east to west, the Sutlej, the Ravi, the Chenab, the Jhelum, the Soan, the Indus, the Swat, the Kabul, and the Haro. It also models the main dams in the system: Tarbela, Mangla, Chasma, and Chotiari. The water is routed through 47 nodes of the Indus system in Pakistan. These nodes include (1) reservoirs, (2) link canals between rivers, and (3) barrages for irrigation outlets. Inflows, precipitation, runoff, and crop water-need data are generated externally by a climate model that is downscaled to Pakistan using historical data. The routing model takes into account river routing time, reservoir evaporation, and link canal capacity.

The model disaggregates the 45 main irrigation canals of the Pakistan Indus basin into 12 agroeconomic zones, based on provinces and crops grown. Four of these zones are in Sindh, five in Punjab, two in Khyber Pakhtunkhwa, and one in Balochistan. Three other zones, in Punjab, Balochistan, and Khyber Pakhtunkhwa, cover the rest of Pakistan. These zones are assumed to have a constant water stress, allowing us to isolate the effects of investments in the Indus basin. Agricultural land area, irrigation capacity, and groundwater pumping are disaggregated to this level. Groundwater pumping is allowed only in nonsaline groundwater areas (each zone is disaggregated into fresh and saline areas, if relevant), though we place a cap on maximum annual abstractions consistent with a sustainable yield for the Indus aquifer (50 MAF, according to Briscoe and Qamar [2005] and Yu et al. [2013]). RWSM-Pak assumes nonirrigation water is drawn from groundwater only. For this study, all water data are drawn from the new Indus Basin Model Revised, developed by the National Engineering Services Pakistan and the WAPDA, while crop data come from the 2010 Agricultural Census of Pakistan (GoP 2010).

The Water Accord of 1991, which reflects a highly sensitive political compromise, dictates the sharing of water between the four provinces and that dams should be managed with irrigation as a priority (Briscoe and Qamar 2005). Implementing the Water Accord in the model leads us to impose rule-based constraints on the simulated system. The objective function is constrained by these stringent rules on dam storage while maximizing the water delivered to cultivated areas. However we do not constrain individual canal releases to follow historical patterns, because this is a usage not enshrined in provincial law. Eight MAF of water are reserved as an outflow to keep the delta healthy, which is also mandated by the Water Accord.

The Hydropower Module

Benefits from the Diamer-Bhasha Dam include not only extra irrigation water but also extra electricity production. We include a hydropower module to simulate the extra electricity that would be produced by the dam. Hydropower generation depends on water flow and head (height of the dam and water level of the reservoir). Given that Pakistan explicitly gives priority to irrigation, we do not include hydropower generation in the objective function of the RWSM-Pak model. Instead, we compute hydropower electricity production after allocating water to the crops and include it as a source of energy in the CGE model.[14] Hydropower is represented as a fixed quantity of the total energy production, because we assume no other hydroelectric dam than Diamer-Bhasha is built. The additional energy production is included in GDP and valued as a benefit of the dam.

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[14] The current CGE model does not disaggregate energy sources or consider substitution possibilities across energy types. More detailed data is currently being developed for the Pakistan SAM and will be included in future models.

Annex B: Discussion of the Translog Stochastic Frontier Production Function

The model used to further investigate the relationship between groundwater and surface water is a translog stochastic frontier production function. The empirical model follows the stochastic frontier model developed by Aigner, Lovell, and Schmidt (1977) and extended by Battese and Coelli (1995). The basic formulation is

$$y_i = x_i\beta + v_i - u_i \qquad (1)$$

for households $i = 1 \ldots N$, where y_i is the natural log of the value of output per unit of land for household i, x_i is a vector of the log of production inputs (fertilizer, capital, pesticide, labor, and the volume of irrigation water—both surface and groundwater estimated separately and as interactions of these variables), and v_i is a zero mean random error, assumed to be independently and identically distributed as $N(0,\sigma_v^2)$. The u_i is a nonnegative random variable associated with the technical inefficiency of production, which measures the percentage of output lost due to inefficiency and is assumed to be distributed as a truncated normal $N^+(u,\sigma_v^2)$. The technical inefficiency component of the error term, u_i, is expressed as $u_i = f(z_i\delta)$, where z_i is a vector of variables thought to explain inefficiency, such as the relative reliance of the household on groundwater compared to surface water, and other controls that can affect technical efficiency. The δ is a vector of associated coefficients to be estimated. The technical efficiency score (TE) of farm i is computed as $TE = \exp(-u_i)$. Thus, the production function component, y_i, and the inefficiency effects, u_i, are estimated together in one step. We have estimated the model for the kharif and rabi seasons separately.

As the previous paragraph indicates, there are two separate estimations included in the single model, one for the production function, and a second for technical inefficiency. The technical efficiency is discussed in depth in the main body of the chapter, with the marginal effects used for that discussion. This annex looks at the production function, which was discussed only briefly in the groundwater section in the chapter, and then presents the full regression model in Table B4.1. Because the dependent variable is the log of value of output per acre, crop mixes are expected to have significant effects, so dummy variables for possible crop combinations grown are included. The final sample size has 618 households in the rabi season and 583 households in kharif.

The production function relates the value of agricultural output per acre in Pakistan to several typical inputs. The results in Table B4.1 show that output

TABLE B4.1 Marginal effects and elasticity of value of output to agricultural inputs in kharif and rabi

	Dependent variable: Log of value of output per acre			
	Kharif		Rabi	
Independent variable	Marginal effects	Implied elasticity	Marginal effects	Implied elasticity
Log of labor days used (days/acre)	0.156*** (0.044)	0.076*** (0.020)	0.097*** (0.024)	0.046*** (0.011)
Log of fertilizer used (kg/acre)	0.124*** (0.045)	0.052*** (0.019)	−0.002 (0.032)	−0.001 (0.015)
Log of machinery hours used per acre	−0.010 (0.049)	0.007 (0.006)	−0.014 (0.034)	0.004 (0.005)
Log of number of sprays used per acre	0.006 (0.039)	0.004 (0.003)	0.021 (0.021)	−0.002 (0.002)
Total groundwater used (inches)	0.045 (0.029)	−0.014* (0.009)	0.022 (0.016)	−0.004 (0.005)
Total surface water used (inches)	−0.011 (0.024)	−0.010 (0.010)	0.019 (0.017)	−0.003 (0.003)
Observations	583	583	618	618

Source: Authors' compilation using data from the RHPS (IFPRI/IDS 2012).

Note: Standard errors in parentheses. Asterisks (*, **, ***) denote significance at the 10, 5, and 1 percent levels, respectively. kg = kilograms.

is responsive to increased labor in agriculture both in kharif and rabi seasons. A 1 percent increase in farm labor days leads to a 0.08 percent increase in the value of output per acre in the kharif season and a 0.05 percent increase in rabi. The effect of additional labor is stronger in kharif, possibly because of the water-intensive nature of kharif crops, with the associated increased labor demand for more water applications, in addition to the higher labor requirements in general for crops in the season. In addition, agricultural production is responsive to increased fertilizer application rates in kharif, as a 1 percent increase in fertilizer application rates leads to a 0.05 percent increase in the value of output per acre in the season.

Table B4.2 shows the complete stochastic frontier production function model results.

TABLE B4.2 Regression results of a stochastic production function and inefficiency effects

	Dependent variable: Log of value of output per acre			
	Kharif		Rabi	
Independent variable	Coefficient	Standard error	Coefficient	Standard error
Log of labor days used (days/acre)	–0.575	(0.446)	0.334	(0.204)
Log of fertilizer used (kg/acre)	0.197	(0.200)	0.152	(0.107)
Log of machinery hours used per acre	0.446	(0.393)	0.296	(0.240)
Log of number of sprays used per acre	–0.276	(0.355)	–0.354	(0.231)
Total groundwater used (inches)	0.159	(0.194)	0.208*	(0.120)
Total surface water used (inches)	0.115	(0.172)	0.102	(0.098)
Labor*fertilizer used	–0.018	(0.035)	–0.016	(0.018)
Labor*capital	–0.063	(0.070)	–0.103***	(0.034)
Labor*pesticide	0.061	(0.054)	0.076***	(0.029)
Labor*groundwater	0.043	(0.031)	–0.006	(0.016)
Labor*surface water	–0.012	(0.027)	0.006	(0.013)
Labor square	0.158*	(0.082)	0.006	(0.033)
Fertilizer*capital	–0.066*	(0.037)	–0.032	(0.024)
Fertilizer*pesticide	–0.007	(0.053)	0.001	(0.036)
Fertilizer*groundwater	–0.022	(0.021)	–0.008	(0.016)
Fertilizer*surface water	-0.027	(0.019)	–0.007	(0.013)
Fertilizer square	0.051**	(0.023)	0.001	(0.017)
Capital*pesticide	0.111*	(0.064)	–0.037	(0.040)
Capital*groundwater	–0.121***	(0.031)	–0.017	(0.027)
Capital*surface water	0.065**	(0.029)	–0.025	(0.020)
Capital square	0.178	(0.118)	0.280***	(0.067)
Pesticide*groundwater	–0.062**	(0.024)	0.021	(0.014)
Pesticide*surface water	-0.008	(0.023)	–0.011	(0.013)
Pesticide square	0.087	(0.055)	–0.018	(0.034)
Groundwater*surface water	0.015	(0.013)	–0.002	(0.008)
Groundwater square	–0.067**	(0.028)	–0.034**	(0.017)
Surface water square	–0.019	(0.028)	–0.028*	(0.017)
Sindh	–0.922***	(0.109)	–0.266***	(0.090)
KPK	–0.646***	(0.198)	–0.163	(0.110)
Constant	11.480***	(1.348)	8.701***	(0.692)
Determinants of technical inefficiency				
Ratio of groundwater to total irrigation water	–0.505**	(0.233)	0.453***	(0.173)
Rainfall was available on the plot	–0.436***	(0.102)	0.073	(0.102)

	Dependent variable: Log of value of output per acre			
	Kharif		Rabi	
Independent variable	Coefficient	Standard error	Coefficient	Standard error
Sindh	−1.408***	(0.268)	−0.211	(0.256)
KPK	−0.168	(0.362)	0.178	(0.202)
Soil and water conservation structure	0.097	(0.097)	0.060	(0.081)
Plot exposed to erosion	0.135	(0.133)	0.072	(0.094)
Canal water not used	0.121	(0.304)	−0.475	(0.299)
Located at the head of the watercourse	−0.288*	(0.158)	0.161	(0.126)
Located at the tail of the watercourse	0.183*	(0.099)	0.239**	(0.110)
Timely supply of canal water (Yes = 1, No = 0)	−0.138	(0.137)	−0.105	(0.137)
Household did not sell any crops in season	−0.101	(0.159)	0.235**	(0.105)
Rented-in plots	0.081	(0.108)	−0.039	(0.091)
Sharecropped-in plots	0.409***	(0.155)	0.164	(0.100)
Minutes to irrigate an acre using canal water	−0.050	(0.049)	−0.021	(0.054)
Flat land	−0.177	(0.164)	−0.146	(0.141)
Slightly sloping land	−0.420**	(0.180)	−0.064	(0.145)
Sandy soil	0.268	(0.202)	0.363**	(0.173)
Sand loam soil	0.014	(0.122)	0.295***	(0.109)
Loam soil	0.019	(0.120)	0.007	(0.101)
Average length of an irrigation turn (minutes)	0.196***	(0.065)	−0.197***	(0.058)
Distance of plot from homestead	0.052*	(0.029)	0.008	(0.027)
Flood irrigation used	0.343***	(0.104)	−0.278**	(0.128)
Khal panchayat exists on the watercourse	−0.313***	(0.112)	−0.497*	(0.263)
Household head attended school	0.077	(0.078)	−0.024	(0.064)
Log of age of household head	0.147*	(0.084)	0.154***	(0.057)
Plots experience waterlogging	0.426***	(0.160)	−0.166	(0.160)
Plots experience salinity	−0.021	(0.173)	−0.067	(0.157)
Producing sorghum only in kharif	0.822***	(0.256)	n.a.	n.a.
Producing cotton only in kharif	0.875***	(0.225)	n.a.	n.a.
Producing cotton and sorghum in kharif	0.787***	(0.217)	n.a.	n.a.
Producing cotton and millet in kharif	0.030	(0.231)	n.a.	n.a.
Producing sugar and sorghum in kharif	−0.103	(0.246)	n.a.	n.a.
Producing other miscellaneous combinations	0.066	(0.202)	n.a.	n.a.
Producing only berseem in rabi	n.a.	n.a.	−0.338	(0.209)
Producing only wheat	n.a.	n.a.	0.319***	(0.102)

(continued)

TABLE B4.2 *(continued)*

	Dependent variable: Log of value of output per acre			
	Kharif		Rabi	
Independent variable	Coefficient	Standard error	Coefficient	Standard error
σ_v	0.176***	(0.024)	0.218***	(0.019)
σ_u	0.639***	(0.035)	0.332***	(0.048)
Observations	583		618	

Source: Authors' estimation.

Note: The rabi crops are wheat and berseem. The kharif crops are rice, cotton, sugarcane, sorghum, and millet. n.a. = not applicable. A negative sign in the coefficients in the bottom panel implies that an increase in the variable reduces technical inefficiency, and hence improves efficiency. Asterisks (*, **, ***) denote significance at the 10, 5, and 1 percent levels, respectively. kg = kilograms; KPK = Khyber Pakhtunkhwa.

Annex C: Income Growth and Distribution in the Simulations

Income effects are presented for six household groups, which have varying levels of dependence on different sectors that affect income, to see how they are affected by climate outcomes and the presence of added storage. Table C4.1 shows the baseline household income for six groups and two forecasted years, 2029 and 2050. Four of the income groups are agriculturally related, including three different farm types (small, medium, and large), with landless agricultural workers as the fourth category. There are two nonagricultural households: nonfarm households in rural areas and urban households. The income of the six household groups from the historical simulation is given in the first column. Nearly 44 percent of total household income goes to urban households, and 23 percent goes to nonagricultural households in rural areas, leaving the farming community with about one-third of total household income. Of that, small farmers receive close to 17 percent, and medium farmers earn 10 percent. The better-off large farmers and agricultural laborers each earn less than 5 percent of the economy's household income. These proportions change only slightly between 2029 and 2050, although average household income grows about 5.2 percent per year after 2029.

The second column shows the annual percentage changes in income to different household groups from the addition of Bhasha Dam. All groups gain except for medium farmers. The small and large farm households see gains relative to the historical scenario of 0.26 percent and 0.30 percent. The nonfarm and urban households, with 0.74 percent gains in income, receive more than twice the rate of gain of farmers. Interestingly, agricultural workers see higher percentage gains in 2029 with Bhasha than do owner-operators. We

TABLE C4.1 Simulations with Bhasha Dam and climate change of annual changes in income from the historical simulation, 2029 and 2050

		Simulation		
	Historical income	Bhasha Dam	CSIRO B1 + Bhasha	MIROC A1B + Bhasha
Household groups	Billions PKR in 2029	Annual change from baseline simulation in 2029 (%)		
Small farms	4,684	0.26	0.08	0.08
Medium farms	2,592	−0.11	−0.47	−0.60
Large farms	1,106	0.30	0.22	0.23
Agricultural workers	850	0.59	0.65	0.74
Nonfarm households	6,514	0.74	0.76	0.88
Urban households	12,786	0.74	0.79	0.92
Total income	**28,532**			
	Billions PKR in 2050	Annual change from baseline simulation in 2050 (%)		
Small farms	13,394	0.87	0.35	0.53
Medium farms	8,084	0.70	0.34	0.36
Large farms	3,155	0.69	0.29	0.48
Agricultural workers	2,354	0.87	0.33	0.67
Nonfarm households	18,352	0.98	0.38	0.75
Urban households	35,305	0.95	0.34	0.73
Total income	**80,644**			

Source: Authors, based on results from the CGE-W model.

Note: The simulations included are Diamer-Bhasha Dam and two climate change scenarios. CSIRO is based on a model of Australia's Commonwealth Scientific and Industrial Research Organization (CSIRO) and MIROC on the Model for Interdisciplinary Research on Climate (MIROC), produced by the University of Tokyo's Center for Climate System Research (following the methodology of Jones and Thornton [2013]). The CSIRO scenario has smaller but more evenly distributed precipitation increases. The MIROC scenario has higher increases in precipitation on average but more variability. PKR = Pakistani rupees.

have controlled for many factors by showing changes relative to the historical model, which makes it clear that varying water availability has important effects on income growth over the longer run.

As before, the climate change scenarios examined are MIROC A1B and CSIRO B1, both with Bhasha Dam included. All farm households lose income as climate change occurs, again with the exception of agricultural workers. With more precipitation and runoff, the average level of the Bhasha reservoir is higher, and more electricity is delivered, which helps industry and services more and leads to higher incomes for nonagricultural households across all three scenarios.

In 2050 a fundamental shift occurs because of the growing demand from population and income versus productivity growth and limits on water and other resources. In this case, all income groups benefit from Bhasha Dam, approaching 1 percent gains in real income in some groups. However, in the CSIRO B1 climate change scenario, all incomes decline by about 0.5 percentage point from the Bhasha simulation alone, even with Bhasha Dam in place. In the higher water supply scenario, MIROC A1B, the decrease is not as great. While evaporation is higher in the MIROC A1B scenario and crop water requirements rise, water availability rises from precipitation and runoff in the July–December period, helping kharif crops in July and August and wheat in the latter months. Thus, incomes are not hurt as much in the MIROC A1B scenario.

Because prices rise by about 30 percent, the annual income growth rate is closer to 4.5 percent. Even if growth rates by household category are roughly the same, absolute values differ if the starting values differ: small farmers have a real income gain of PKR 8.7 trillion, while urban households gain PKR 11.8 trillion, with about the same percentage of additions to income.

Next, we explore income distribution effects related to watercourse efficiency improvements and agricultural productivity gains. The baseline values of income for the six household groups shown in the first column of Table C4.2 are similar to the earlier climate change simulations, but they change somewhat because of the use of an updated model. The next columns show percentage changes in income relative to the baseline scenario in 2029 and 2050 for the same options examined for GDP and water allocation. The highest gains to households in individual simulations are from BDAM in 2029 and TMG in 2050. The highest growth in household income in combination simulations occurs in the combinations of BDAM and TMG. In the latter case, real income gains exceed 0.50 percent for some household groups. While seemingly not large, a 0.30 percent difference in growth rates per year would lead to an 81 percent income differential over 20 years. Also, as noted in the earlier section on income distribution, when initial levels of income differ, equal percentage growth rates create a widening absolute gap.

For individual simulations, BDAM and TMG show significant gains across all household groups (except for TMG for medium farms in 2029). For the WCE simulation, however, farmers lose while other income groups gain, and this simulation adds the least to income, both in 2029 and 2050. The differences across households are smaller for these alternatives than in the climate change results because total water available does not vary. As before, agricultural workers see higher gains in both years and for all simulations compared to owner-operators.

TABLE C4.2 Alternative simulations of annual changes in income from the baseline simulation, 2029 and 2050

		Simulation					
	Base income	BDAM	TMG	WCE	BDAM + WCE	TMG + WCE	BDAM + TMG
Household groups	Billions PKR in 2029	Annual change from baseline simulation in 2029					
Small farms	4,612	0.30	0.08	−0.04	0.27	0.04	0.22
Medium farms	2,563	0.25	−0.14	−0.20	0.22	−0.13	0.35
Large farms	1,090	0.33	0.14	−0.01	0.27	0.08	0.40
Agricultural workers	834	0.40	0.29	0.13	0.37	0.22	0.54
Nonfarm households	6,326	0.45	0.36	0.12	0.41	0.27	0.62
Urban households	12,432	0.43	0.37	0.14	0.38	0.28	0.60
Total income	**27,857**						
	Billions PKR in 2050	Annual change from baseline simulation in 2050					
Small farms	12,942	0.19	0.23	−0.08	0.11	0.17	0.13
Medium farms	7,680	0.11	0.19	−0.22	0.03	0.07	0.31
Large farms	3,050	0.23	0.31	−0.04	0.12	0.21	0.37
Agricultural workers	2,298	0.31	0.39	0.10	0.24	0.32	0.55
Nonfarm households	17,634	0.34	0.43	0.06	0.25	0.35	0.58
Urban households	34,130	0.33	0.43	0.10	0.24	0.36	0.58
Total income	**77,734**						

Source: Authors, based on results from the CGE-W model.

Note: The simulations included are BDAM, Diamer-Bhasha Dam; TMG, better timing of water applications; and WCE, reduced seepage losses in watercourses. Three of these scenarios are combined: BDAM + WCE, TMG + WCE, and BDAM + TMG. CGE-W = computable general equilibrium-water

The individual simulations contribute varying amounts in 2029 and 2050. BDAM's contribution comes early because of immediate additions of hydropower and water, but it does not grow over time. As such, the rate of growth in household income is less in 2050 than in 2029. In contrast, TMG's income contributions are higher in later years as the value of better yields grows with the scarcity of resources. While WCE's contribution is low in both years, we find opposite conclusions in the microeconomic analysis.